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THE KNOCK-LIMITED PERFORMANCE OF FUEL BLENDS CONTAINING AROMATICS

III - 1,3,5-TRIMETHYLBENZENE, tert-BUTYLBENZENE AND 1,2,4-TRIMETHYLBENZENE

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NACA

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ADVANCE RESTRICTED REPORT

THE KNOCK-LIMITED PERFORMANCE OF FUEL BLENDS CONTAINING AROMATICS

III - 1,3,5-TRIMETHYLBENZENE, tert-BUTYLBENZENE AND 1,2,4-TRIMETHYLBENZENE

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SUMMARY

Knock-limited small-scale-engine tests were made of 1,3,5-trimethylbenzene, tert-butylbenzene, and 1,2,4-trimethylbenzene blended individually in various concentrations with selected base fuels. Data were obtained for the aromatics to determine: (a) the blending sensitivity, (b) the lead susceptibility, and (c) the sensitivity of the blends to inlet-air temperature. Published full-scale-cylinder data for the aromatics are presented for comparative purposes.

The data indicate that tert-butylbenzene was usually more effective than 1,3,5-trimethylbenzene in increasing the knock-limited power of the base fuels at lean mixtures; 1,3,5-trimethylbenzene was more effective at rich mixtures. 1,2,4-Trimethylbenzene decreased the knock-limited power of the base fuels at lean mixtures under all conditions tested and was never so effective as the other two aromatics in the rich region.

INTRODUCTION

An investigation to determine the effectiveness of aromatic hydrocarbons as antiknock blending agents for aviation fuels is being conducted by the NACA at the Cleveland laboratory. A comprehensive description of the program and its over-all objectives are presented in reference 1. In brief, the program consists in determining: (a) the blending sensitivity of the aromatic in base reference fuels, (b) the lead susceptibility of the aromatic blends, (c) the sensitivity of the aromatic blends to inlet-air temperature, and (d) the correlation of full-scale and small-scale engine results.

Samples of several aromatic hydrocarbons were synthesized, or purchased, and purified in the Organic Synthesis Section of the Fuels and Lubricants Division. Each aromatic, after purification, was individually blended with selected base fuels. Knock-limited performance data obtained with F-3, F-4, and 17.6 engines for six of the aromatics are presented in references 1 and 2. Similar small-scale-engine data for 1,3,5-trimethylbenzene (mesitylene), tert-butylbenzene, and 1,2,4-trimethylbenzene (pseudocumene) are presented in this report, which is part III of a series of five reports covering the above program. In references 1 and 2, as well as in the present report, R-1820 G200 single-cylinder-engine data from reference 3 are included to facilitate comparison of small-scale and full-scale engine results.

APPARATUS, FUELS, AND TEST PROCEDURE

A description of the engines and the engine conditions used for the tests may be found in reference 1 for the 17.6 engine, the F-3 engine, and the "research" F-4 engine. The F-4 engine is not a package unit but is operated under F-4 test conditions and called the F-4 engine throughout this series of reports.

The physical constants for purified samples of the three aromatics tested are presented in the following table and serve to indicate the purity of the samples used:

Aromatic	Freezing point (°C)	Boiling point (°C)	Index of refraction n_D^{20}	Density at 20° C (gram/ml)
1,3,5-Trimethylbenzene	-45.30	164.9	1.4990	0.8649
tert-Butylbenzene	-57.96	169.2	1.4926	.8663
1,2,4-Trimethylbenzene	-44.27	169.4	1.5048	.8757

The composition of the test fuel blends and an outline of the tests with the 17.6 and F-4 engines are given in the following table:

Engine	Inlet-air temperature (°F)	Percentage aromatic in blend	Base Fuel	Tetraethyl lead in final blend (ml/gal)
17.6	250	0,10,20	S-3	0
	100	0,20	S-3	0
	250	0,10,20	S-3	4
	100	0,20	S-3	4
	250	0,25	85% S-3 + 15% M-4	4
	100	0,25	85% S-3 + 15% M-4	4
F-4	225	0,10,25,50	85% S-3 + 15% M-4	4

Whenever quantity permitted, the blends were also tested in the F-3 engine.

PRESENTATION AND DISCUSSION OF RESULTS

The results are presented and discussed in two principal divisions: (a) F-4 and F-3 engine data, and (b) 17.6 engine data. An index of figures showing in detail the order of discussing tests and results in this paper is given in table I.

F-4 and F-3 engine data. - The knock-limited performance of the base fuel (85 percent S-3 plus 15 percent M-4 plus 4 ml TEL/gal) in the F-4 engine is presented in figure 1 (reproduced from fig. 7 of reference 1), and the results for blends of 10, 25, and 50 percent aromatics with this base fuel are shown in figures 2, 3, and 4 for 1,3,5-trimethylbenzene, *tert*-butylbenzene, and 1,2,4-trimethylbenzene, respectively.

Figures 5, 6, and 7 are graphs showing the variation of knock-limited imep ratio $\left(\text{imep ratio} = \frac{\text{imep of aromatic blend}}{\text{imep of base fuel}}\right)$ with aromatic concentration for the blends tested with the F-4 engine. The antiknock qualities of the three aromatics, when tested at relatively severe engine conditions (F-4), are well illustrated in these figures. At lean fuel-air mixtures, the knock-limited performance of the aromatic blends was poor in comparison with that of the base fuel; at rich mixtures, additions of 1,3,5-trimethylbenzene or *tert*-butylbenzene resulted in large percentage increases in the knock-limited power of the base fuel. As the aromatic concentration was changed from 25 to 50 percent, at a fuel-air ratio of 0.10 the rate of increase in the knock-limited imep ratio increased. This rate of increase, also observed for other aromatics (references 1 and 2), was of a much greater magnitude for 1,3,5-trimethylbenzene and *tert*-butylbenzene than for 1,2,4-trimethylbenzene.

The E-4 and the F-3 ratings of the various blends are recorded in table II in terms of S-3 plus tetraethyl lead or octane number; all ratings are also given as accepted Army-Navy performance numbers.

17.6 engine data. - The knock-limited performance in the 17.6 engine of blends containing the aromatics with either the S-3 reference fuel or the S-3 plus M-4 base fuel are presented in figures 8 to 10 for 1,3,5-trimethylbenzene, in figures 11 to 13 for tert-butylbenzene, and in figures 14 to 16 for 1,2,4-trimethylbenzene. The data are presented in the following order for each aromatic: unleaded blends with S-3, leaded blends with S-3, and leaded blends with the S-3 plus M-4 base fuel; inlet-air temperatures of 250° and 100° F were used. This order conforms with that in which the tests were conducted. Each graph presents data obtained during a single operating day.

In unleaded S-3 blends at an inlet-air temperature of 250° F, additions of 1,3,5-trimethylbenzene (fig. 8(a)) and tert-butylbenzene (fig. 11(a)) failed to increase the knock-limited power of the base fuel at fuel-air mixtures leaner than 0.07, but substantial rich-mixture improvements were observed. At an inlet-air temperature of 100° F (figs. 8(b) and 11(b)), both aromatics were effective antiknock agents at all fuel-air ratios tested. 1,2,4-Trimethylbenzene (fig. 14) acted as a proknock agent at fuel-air ratios below 0.105 at the higher inlet-air temperature and at fuel-air ratios below 0.08 at the lower inlet-air temperature.

In leaded blends with S-3 at an inlet-air temperature of 250° F, additions of 1,3,5-trimethylbenzene (fig. 9(a)) and tert-butylbenzene (fig. 12(a)) increased the knock-limited power of the base fuel at all fuel-air ratios tested. The lead response of blends containing these two aromatics was also noted at an inlet-air temperature of 100° F. (See figs. 9(b) and 12(b).) At both inlet-air temperatures and with few exceptions, greater percentage decreases in knock-limited power relative to the base fuel were observed for the leaded (fig. 15) than for the unleaded (fig. 14) 1,2,4-trimethylbenzene blends.

The knock-limited performance of the 25-percent leaded blends of the aromatics with the S-3 plus M-4 base fuel at inlet-air temperatures of 250° and 100° F are presented in figures 10, 13, and 16. The addition of either 1,3,5-trimethylbenzene and tert-butylbenzene increased the knock-limited power of the base fuel at all fuel-air ratios tested and for both inlet-air temperatures. 1,2,4-Trimethylbenzene decreased the knock-limited power of the

base fuel at fuel-air ratios below 0.08 at the higher inlet-air temperature and at fuel-air ratios below 0.07 at the lower inlet-air temperature.

In general, tert-butylbenzene was more effective in increasing the knock-limited indicated mean effective pressures of the base fuels at lean fuel-air mixtures than was 1,3,5-trimethylbenzene, which was in most instances more effective at rich fuel-air mixtures. In contrast to these two aromatic hydrocarbons, it should be noted that 1,2,4-trimethylbenzene decreased the knock-limited power of the base fuels at lean mixtures under all conditions tested and was never so effective as the other two aromatics at rich mixtures.

Figures 17, 18, and 19 are graphs of knock-limited imep ratio against aromatic concentration for the blends of the aromatics with S-3 tested in the 17.6 engine. The comparative effect of the addition of each of the aromatic hydrocarbons at fuel-air ratios of 0.07, 0.085, and 0.10 as well as the effect of inlet-air temperature and tetraethyl-lead additions are shown by these data. The trends are in general agreement with those in figures 5, 6, and 7.

The temperature sensitivities of the aromatic blends relative to that of the base fuel are summarized in table III. With few exceptions the aromatic blends were more sensitive to changes of inlet-air temperature than were the base fuels although, as the fuel-air mixture was enriched, the temperature sensitivity of the aromatic blends in most cases approached that of the base fuel.

Data on the lead susceptibility of the aromatic blends relative to that of S-3 reference fuel are given in table IV. The lead susceptibilities of blends containing 1,3,5-trimethylbenzene or tert-butylbenzene were in nearly all cases greater than that of S-3 reference fuel. The response of 1,2,4-trimethylbenzene blends to an addition of tetraethyl lead was, with some exceptions, less than that of S-3.

Summary of engine data. - A summary of the knock-limited data obtained with the 17.6 engine, the full-scale cylinder (from reference 3), and the F-4 engine is presented in table V. In order to calculate the knock-limited imep ratios presented therein, it was necessary to determine the daily performance of the base fuel. Because the S-3 plus M-4 base fuel was not tested each day in the F-4 engine, the daily knock-limited performance curve for this fuel was estimated from the available daily performance of S-3 and S-3 plus tetraethyl lead and from the data in figure 1.

SUMMARY OF RESULTS

From knock-limited tests of fuel blends containing 1,3,5-trimethylbenzene, tert-butylbenzene, or 1,2,4-trimethylbenzene, the following results were obtained:

1. tert-Butylbenzene was usually more effective than 1,3,5-trimethylbenzene in increasing the knock-limited power of the base fuels at lean fuel-air mixtures; 1,3,5-trimethylbenzene was more effective at rich mixtures. 1,2,4-Trimethylbenzene decreased the knock-limited power of the base fuels at lean mixtures under all conditions tested and was never so effective as the other two aromatics in the rich region.

2. The knock-limited performance of the aromatic blends was generally more sensitive to changes of inlet-air temperature than that of the base fuels.

3. The data indicate that blends containing either 1,3,5-trimethylbenzene or tert-butylbenzene had greater lead susceptibilities than S-3 reference fuel; blends containing 1,2,4-trimethylbenzene had lower lead susceptibility than S-3 in most cases.

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3. Bull, Arthur W., and Jones, Anthony W.: Knock-Limited Performance of Pure Hydrocarbons Blended with a Base Fuel in a Full-Scale Aircraft-Engine Cylinder. II - Twelve Aromatics. NACA ARR No. E4I09, 1944.

TABLE I. - INDEX OF FIGURES

Figure	Compound	Percentage aromatic in the blend	Base fuel	Lead concentration (ml/gal)	Inlet-air temperature (°F)
F-4 engine (knock-limited imep against fuel-air ratio)					
1	-----------------	0	85% S-3 + 15% M-4	4	225
2(a) (b) (c)	1,3,5-Trimethyl-benzene	10 25 50	85% S-3 + 15% M-4	4	225
3(a) (b) (c)	tert-Butylbenzene	10 25 50	85% S-3 + 15% M-4	4	225
4(a) (b) (c)	1,2,4-Trimethyl-benzene	10 25 50	85% S-3 + 15% M-4	4	225
F-4 engine (knock-limited imep ratio against aromatic concentration)					
5	1,3,5-Trimethyl-benzene	0,10,25,50	85% S-3 + 15% M-4	4	225
6	tert-Butylbenzene	0,10,25,50	85% S-3 + 15% M-4	4	225
7	1,2,4-Trimethyl-benzene	0,10,25,50	85% S-3 + 15% M-4	4	225
17.6 engine (knock-limited imep against fuel-air ratio)					
8(a) (b)	1,3,5-Trimethyl-benzene	0,10,20 0,20	S-3	0	250 100
9(a) (b)	1,3,5-Trimethyl-benzene	0,10,20 0,20	S-3	4	250 100
10	1,3,5-Trimethyl-benzene	0,25	85% S-3 + 15% M-4	4	250
11(a) (b)	tert-Butylbenzene	0,10,20 0,20	S-3	0	250 100
12(a) (b)	tert-Butylbenzene	0,10,20 0,20	S-3	4	250 100
13(a) (b)	tert-Butylbenzene	0,25 0,25	85% S-3 + 15% M-4	4	250 100
14(a) (b)	1,2,4-Trimethyl-benzene	0,10,20 0,20	S-3	0	250 100
15(a) (b)	1,2,4-Trimethyl-benzene	0,10,20 0,20	S-3	4	250 100
16(a) (b)	1,2,4-Trimethyl-benzene	0,25 0,25	85% S-3 + 15% M-4	4	250 100
17.6 engine (knock-limited imep ratio against aromatic concentration)					
17	1,3,5-Trimethyl-benzene	0,10,20	S-3	0,4	250,100
18	tert-Butylbenzene	0,10,20	S-3	0,4	250,100
19	1,2,4-Trimethyl-benzene	0,10,20	S-3	0,4	250,100

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TABLE II - F-4 AND F-3 RATINGS OF 1,3,5-TRIMETHYLBENZENE

tert-BUTYLBENZENE, AND 1,2,4-TRIMETHYLBENZENE BLENDS

Compound	Blend composition (percent by volume)			Tetraethyl lead (ml/gal)	F-4 ratings				F-3 ratings	
					Lean		Rich			
	Pure aromatic	S-3 reference fuel	85 percent S-3 plus 15 percent M-4		S-3 + ml TEL	Performance number	S-3 + ml TEL	Performance number	S-3 + ml TEL	Performance number
Base fuel	0	0	100	4	0.36	112	0.26	109	0.39	113
1,3,5-Trimethylbenzene	10	0	90	4	0.37	112	1.55	134	0.53	117
tert-Butylbenzene	10	0	90	4	.87	123	1.28	130	.63	119
1,2,4-Trimethylbenzene	10	0	90	4	.20	107	.05	102	.18	107
1,3,5-Trimethylbenzene	25	0	75	4	0.32	111	>6.00	--------	0.76	121
tert-Butylbenzene	25	0	75	4	.98	125	5.72	160	.77	122
1,2,4-Trimethylbenzene	25	0	75	4	.00	100	.31	111	[a]98.8	96
1,3,5-Trimethylbenzene	50	0	50	4	0.50	116	>6.00	--------	------	--------
tert-Butylbenzene	50	0	50	4	.45	114	>6.00	--------	0.80	122
1,2,4-Trimethylbenzene	50	0	50	4	.13	105	3.71	151	[a]98.0	93
1,3,5-Trimethylbenzene	10	90	0	4	------	--------	------	--------	3.50	150
tert-Butylbenzene	10	90	0	4	------	--------	------	--------	3.77	151
1,2,4-Trimethylbenzene	10	90	0	4	------	--------	------	--------	2.25	141
tert-Butylbenzene	20	80	0	4	------	--------	------	--------	2.43	142
1,2,4-Trimethylbenzene	20	80	0	4	------	--------	------	--------	.72	121
tert-Butylbenzene	10	90	0	0	------	--------	------	--------	[a]99.5	98
1,2,4-Trimethylbenzene	10	90	0	0	------	--------	------	--------	[a]97.2	91
tert-Butylbenzene	20	80	0	0	------	--------	------	--------	[a]99.8	99
1,2,4-Trimethylbenzene	20	80	0	0	------	--------	------	--------	[a]95.8	87

[a]Octane number.

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TABLE III - TEMPERATURE SENSITIVITY OF 1,3,5-TRIMETHYLBENZENE, tert-BUTYLBENZENE, AND 1,2,4-TRIMETHYLBENZENE BLENDS RELATIVE TO THAT OF THE BASE FUELS

[17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; outlet-coolant temperature, 212° F; spark advance, 30° B.T.C.]

Compound	Blend composition (percent by volume)			Tetraethyl lead (ml/gal)	Relative temperature sensitivity[a]				
	Pure aromatic	S-3 reference fuel	85 percent S-3 plus 15 percent M-4		Fuel-air ratio				
					0.065	0.07	0.085	0.10	0.11
S-3	0	100	0	0	1.00	1.00	1.00	1.00	1.00
1,3,5-Trimethylbenzene	20	80	0	0	1.26	1.22	1.21	1.17	1.06
tert-Butylbenzene	20	80	0	0	1.31	1.29	1.22	1.23	1.13
1,2,4-Trimethylbenzene	20	80	0	0	1.10	1.10	1.12	1.11	1.05
S-3	0	100	0	4	1.00	1.00	1.00	1.00	1.00
1,3,5-Trimethylbenzene	20	80	0	4	1.24	1.21	1.20	1.11	1.05
tert-Butylbenzene	20	80	0	4	1.04	1.05	1.06	1.04	1.01
1,2,4-Trimethylbenzene	20	80	0	4	1.04	1.02	.99	1.00	1.01
85 percent S-3 + 15 percent M-4	0	0	100	4	1.00	1.00	1.00	1.00	1.00
1,3,5-Trimethylbenzene	25	0	75	4	-----	-----	-----	-----	-----
tert-Butylbenzene	25	0	75	4	1.18	1.25	1.15	1.09	1.07
1,2,4-Trimethylbenzene	25	0	75	4	1.12	1.08	1.03	1.01	1.01

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$$^{a}\text{Relative temperature sensitivity} = \frac{\dfrac{\text{imep of aromatic blend (inlet-air temperature, } 100^{\circ}\text{ F)}}{\text{imep of aromatic blend (inlet-air temperature, } 250^{\circ}\text{ F)}}}{\dfrac{\text{imep of base fuel (inlet-air temperature, } 100^{\circ}\text{ F)}}{\text{imep of base fuel (inlet-air temperature, } 250^{\circ}\text{ F)}}}$$

$$= \frac{\text{imep ratio (inlet-air temperature, } 100^{\circ}\text{ F)}}{\text{imep ratio (inlet-air temperature, } 250^{\circ}\text{ F)}}.$$

TABLE IV - LEAD SUSCEPTIBILITY OF 1,3,5-TRIMETHYLBENZENE, tert-BUTYLBENZENE, AND 1,2,4-TRIMETHYLBENZENE BLENDS RELATIVE TO THAT OF S-3 REFERENCE FUEL

[17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; outlet-coolant temperature, 212° F; spark advance, 30° B.T.C.]

Compound	Inlet-air temperature (°F)	Composition (percent by volume)		Relative lead susceptibility[a]				
				Fuel-air ratio				
		Pure aromatic	S-3 reference fuel	0.065	0.07	0.085	0.10	0.11
S-3	250	0	100	1.00	1.00	1.00	1.00	1.00
1,3,5-Trimethylbenzene	250	10	90	1.04	1.05	1.09	1.01	0.97
tert-Butylbenzene	250	10	90	1.14	1.12	1.07	1.04	.99
1,2,4-Trimethylbenzene	250	10	90	1.00	1.01	1.02	.96	.93
1,3,5-Trimethylbenzene	250	20	80	1.12	1.13	1.15	1.10	1.04
tert-Butylbenzene	250	20	80	1.39	1.37	1.21	1.18	1.11
1,2,4-Trimethylbenzene	250	20	80	.98	1.02	1.04	.98	.90
S-3	100	0	100	1.00	1.00	1.00	1.00	1.00
1,3,5-Trimethylbenzene	100	20	80	1.10	1.11	1.14	1.05	1.03
tert-Butylbenzene	100	20	80	1.10	1.11	1.05	1.00	.99
1,2,4-Trimethylbenzene	100	20	80	.92	.95	.92	.88	.86

[a]Relative lead susceptibility $= \dfrac{\dfrac{\text{imep of aromatic blend (with 4 ml TEL/gal)}}{\text{imep of aromatic blend (with 0 ml TEL/gal)}}}{\dfrac{\text{imep of S-3 (with 4 ml TEL/gal)}}{\text{imep of S-3 (with 0 ml TEL/gal)}}}$

$= \dfrac{\text{imep ratio of aromatic blend (with 4 ml TEL/gal)}}{\text{imep ratio of aromatic blend (with 0 ml TEL/gal)}}.$

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TABLE I. - SUPERCHARGED-ENGINE TESTS OF BLENDS CONTAINING 1,3,5-TRIMETHYLBENZENE, tert-BUTYLBENZENE, OR 1,2,4-TRIMETHYLBENZENE

Fuel composition					Engine conditions		Test results									
	Blend composition (percent by volume)			Tetra-ethyl lead (ml/gal)			Fuel-air ratio									
							0.065		0.07		0.085		0.10		0.11	
Compound	Pure aromatic	S-3 reference fuel	85 percent S-3 plus 15 percent M-4		Engine speed (rpm)	Inlet-air temperature (°F)	imep	imep ratio[a]	imep	imep ratio[a]	imep	imep ratio[a]	imep	imep ratio[a]	imep	imep ratio[a]
17.6 engine																
1,3,5-Trimethylbenzene	10	90	0	0	1800	250	118	0.96	121	0.98	144	1.03	179	1.15	193	1.21
tert-Butylbenzene	10	90	0	0			107	.98	110	1.00	135	1.05	169	1.12	163	1.19
1,2,4-Trimethylbenzene	10	90	0	0			96	.91	99	.93	120	.95	148	.99	154	1.01
1,3,5-Trimethylbenzene	20	80	0	0	1800	250	112	0.91	116	0.95	151	1.08	198	1.27	225	1.42
tert-Butylbenzene	20	80	0	0			104	.95	105	.95	139	1.08	173	1.15	196	1.27
1,2,4-Trimethylbenzene	20	80	0	0			91	.87	92	.66	115	.91	143	.96	160	1.05
1,3,5-Trimethylbenzene	20	80	0	0	1800	100	170	1.15	168	1.16	206	1.31	238	1.48	244	1.51
tert-Butylbenzene	20	80	0	0			176	1.24	172	1.23	199	1.32	224	1.41	226	1.43
1,2,4-Trimethylbenzene	20	80	0	0			135	.96	132	.95	153	1.02	172	1.07	177	1.10
1,3,5-Trimethylbenzene	10	90	0	4	1800	250	188	1.00	203	1.03	251	1.12	286	1.16	291	1.17
tert-Butylbenzene	10	90	0	4			208	1.12	217	1.12	252	1.12	286	1.16	292	1.18
1,2,4-Trimethylbenzene	10	90	0	4			170	.91	185	.94	221	.97	234	.95	232	.94
1,3,5-Trimethylbenzene	20	80	0	4	1800	250	192	1.02	211	1.07	278	1.24	344	1.40	364	1.47
tert-Butylbenzene	20	80	0	4			245	1.32	252	1.30	293	1.31	334	1.36	350	1.41
1,2,4-Trimethylbenzene	20	80	0	4			159	.85	173	.88	215	.95	232	.94	231	.94
1,3,5-Trimethylbenzene	20	80	0	4	1800	100	335	1.26	340	1.29	400	1.49	419	1.55	413	1.55
tert-Butylbenzene	20	80	0	4			366	1.37	360	1.36	377	1.39	384	1.41	380	1.42
1,2,4-Trimethylbenzene	20	80	0	4			232	.88	235	.90	253	.94	255	.94	255	.95
1,3,5-Trimethylbenzene	25	0	75	4	1800	250	139	1.13	161	1.22	228	1.45	270	1.58	280	1.66
tert-Butylbenzene	25	0	75	4			159	1.24	165	1.22	214	1.34	242	1.41	245	1.44
1,2,4-Trimethylbenzene	25	0	75	4			113	.86	127	.92	162	1.01	179	1.03	177	1.05
1,3,5-Trimethylbenzene	25	0	75	4	1800	100	-----	-------	-----	-------	-----	-------	-----	-------	-----	------
tert-Butylbenzene	25	0	75	4			232	1.46	241	1.52	268	1.54	275	1.54	271	1.54
1,2,4-Trimethylbenzene	25	0	75	4			156	.96	161	.99	184	1.04	188	1.04	188	1.06
Full-scale cylinder (data from reference 3)																
1,3,5-Trimethylbenzene	25	0	75	4	2500	250	184	1.19	196	1.25	304	1.63	371	1.72	-----	------
tert-Butylbenzene	25	0	75	4			192	1.24	204	1.30	281	1.50	331	1.53	352	1.52
1,2,4-Trimethylbenzene	25	0	75	4			136	.88	136	.87	208	1.11	238	1.10	255	1.10
1,3,5-Trimethylbenzene	25	0	75	4	2000	210	199	1.34	210	1.39	282	1.54	344	1.62	372	1.64
tert-Butylbenzene	25	0	75	4			220	1.49	225	1.49	287	1.57	331	1.55	338	1.49
1,2,4-Trimethylbenzene	25	0	75	4			110	.74	132	.87	193	1.05	229	1.08	244	1.07
F-4 engine																
1,3,5-Trimethylbenzene	10	0	90	4	1800	225	114	1.09	128	1.10	171	1.13	197	1.16	203	1.18
tert-Butylbenzene	10	0	90	4			137	1.06	147	1.06	180	1.10	197	1.14	201	1.15
1,2,4-Trimethylbenzene	10	0	90	4			120	.92	134	.95	160	.98	169	.98	170	.97
1,3,5-Trimethylbenzene	25	0	75	4	1800	225	96	.94	109	.95	191	1.26	233	1.39	255	1.49
tert-Butylbenzene	25	0	75	4			144	1.12	162	1.17	213	1.31	246	1.42	258	1.47
1,2,4-Trimethylbenzene	25	0	75	4			101	.81	117	.85	161	1.02	174	1.03	176	1.02
1,3,5-Trimethylbenzene	50	0	50	4	1800	225	104	1.02	120	1.04	242	1.61	[b]480	[b]2.86	-----	------
tert-Butylbenzene	50	0	50	4			119	1.06	141	1.13	230	1.46	393	2.28	452	2.58
1,2,4-Trimethylbenzene	50	0	50	4			100	.81	114	.83	166	1.04	206	1.21	230	1.34

[a] $\text{imep ratio} = \dfrac{\text{imep of aromatic blend}}{\text{imep of base fuel}}$. For the blends tested in the 17.6 engine, the base fuel was S-3, S-3 plus 4 ml TEL/gal, or 85 percent S-3 plus 15 percent M-4 plus 4 ml TEL/gal; in all other instances, 85 percent S-3 plus 15 percent M-4 plus 4 ml TEL/gal was used.

[b] Estimated.

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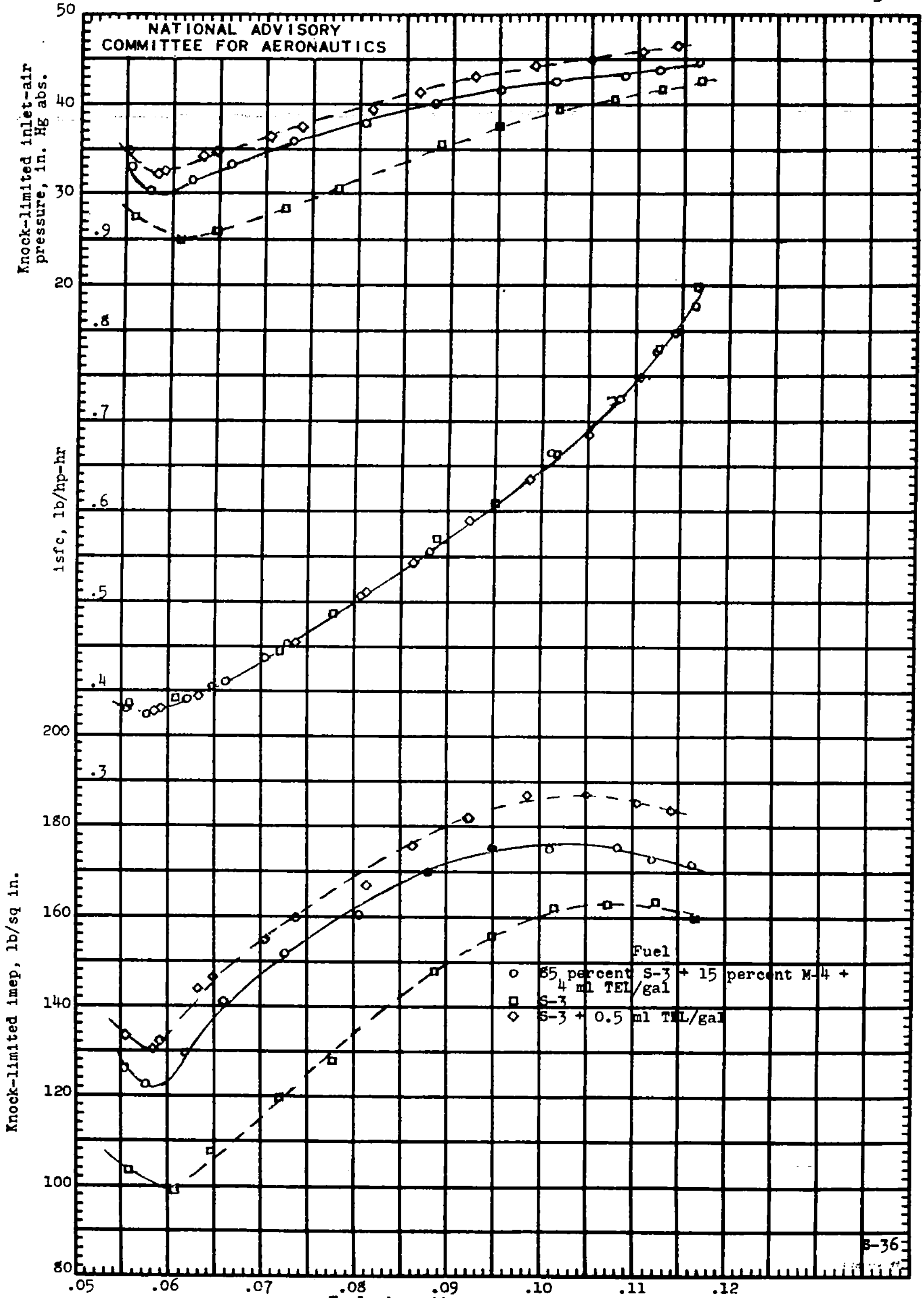
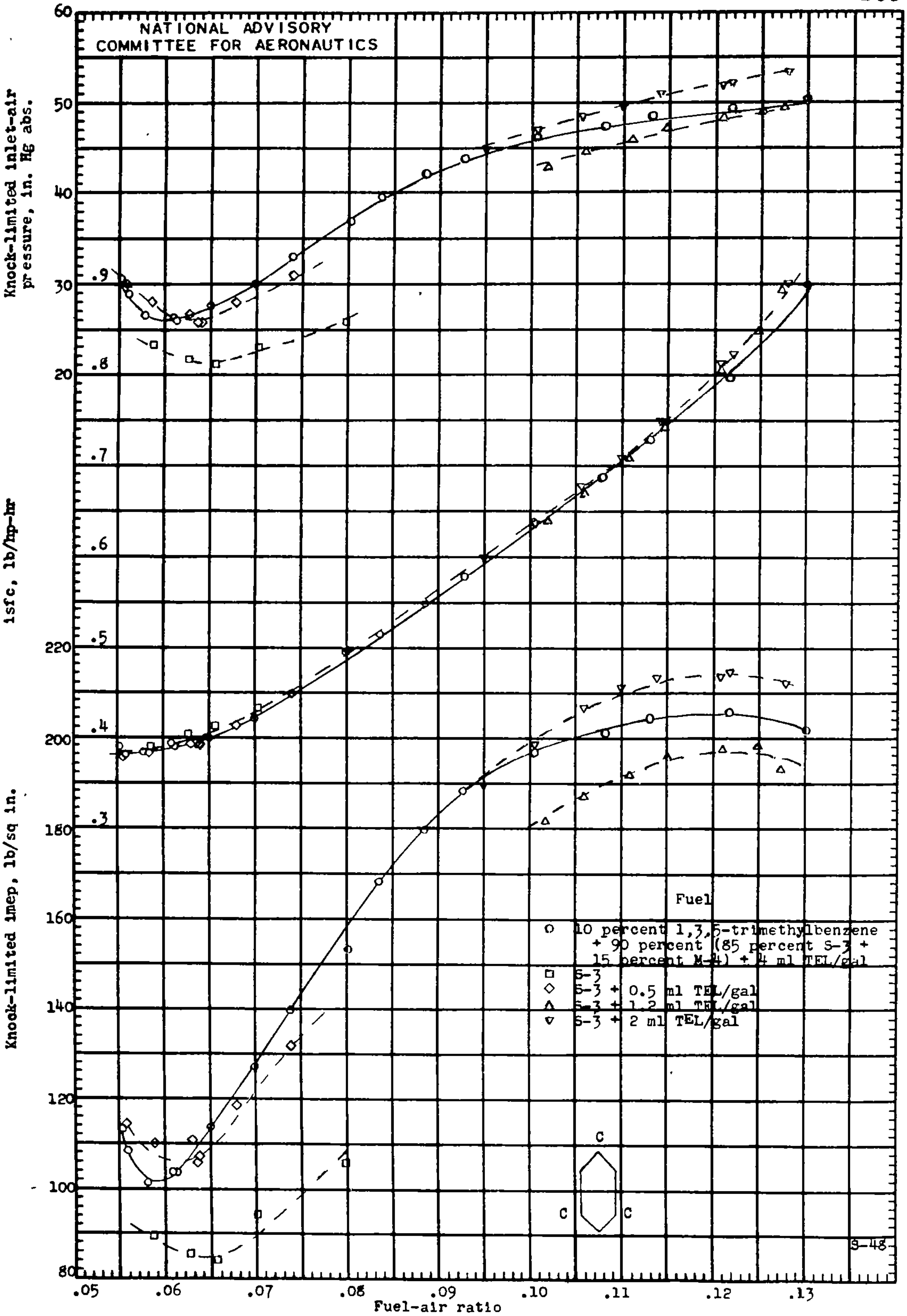
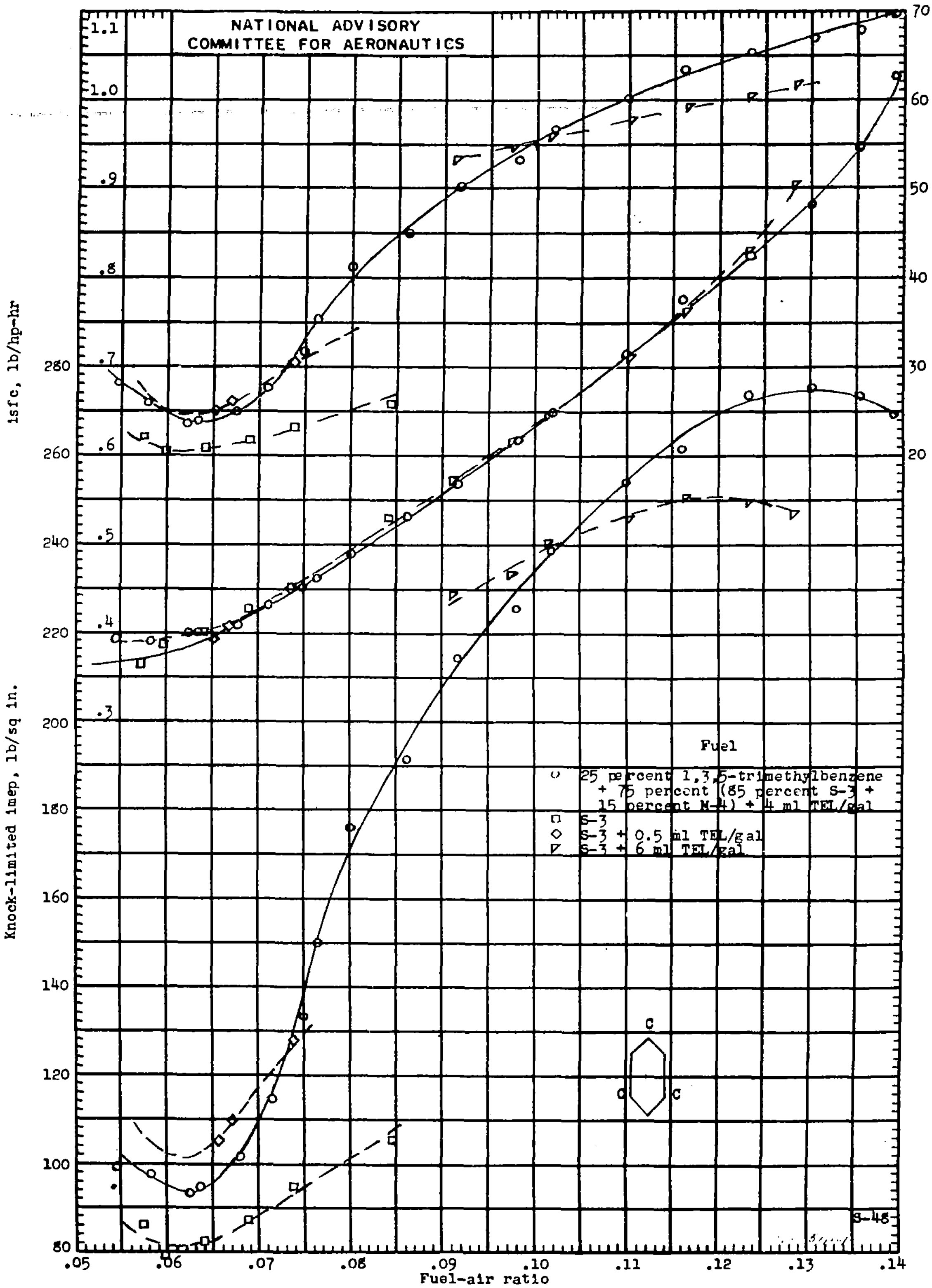


Figure 1. - Knock-limited performance of 85 percent S-3 plus 15 percent M-4 plus 4 ml TEL per gallon in an F-4 engine. (Reproduced from fig. 7 of reference 1.)

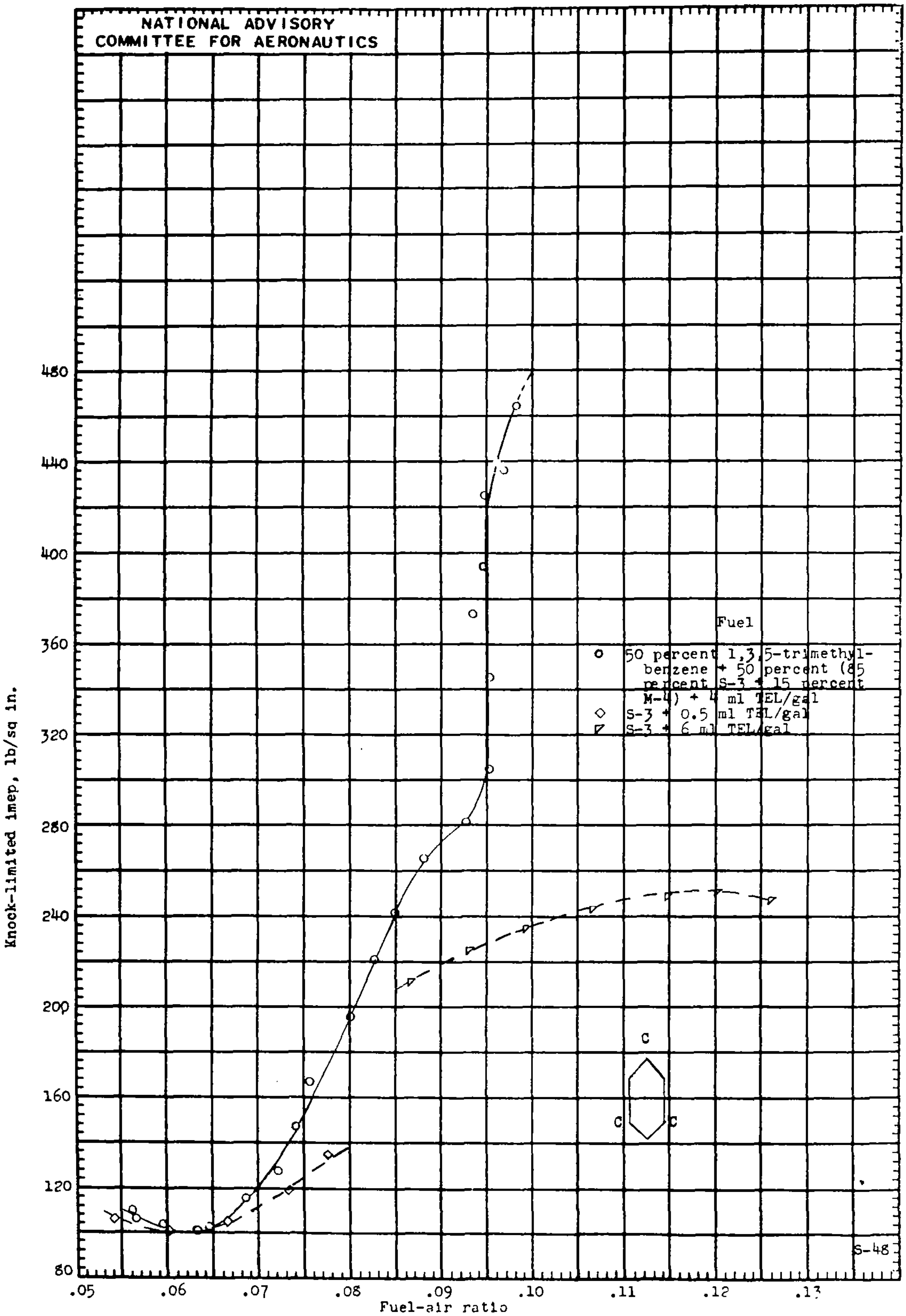


(a) 10 percent 1,3,5-trimethylbenzene plus 90 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per gallon.

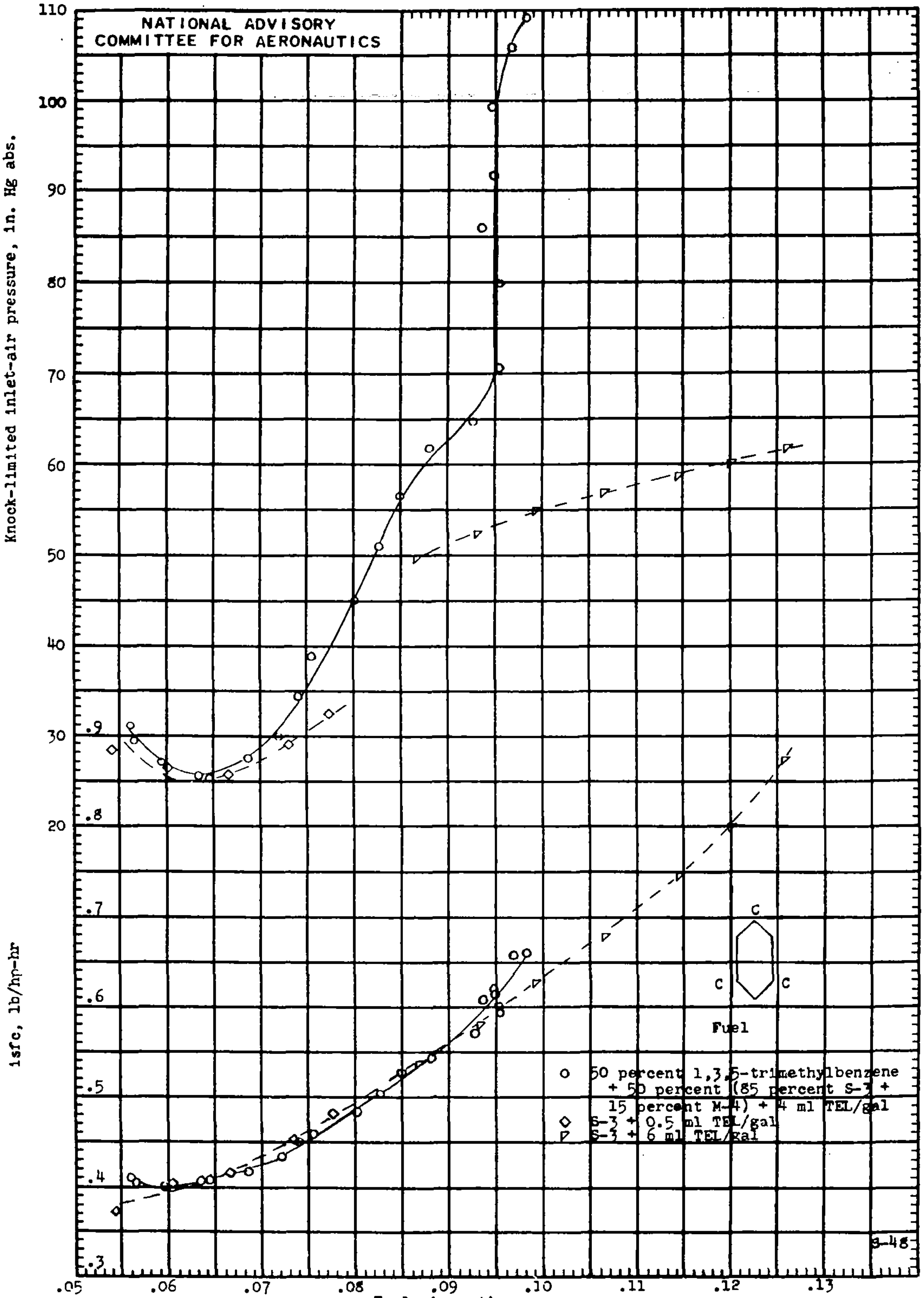
Figure 2. - Knock-limited performance of blends containing 1,3,5-trimethylbenzene in an F-4 engine.



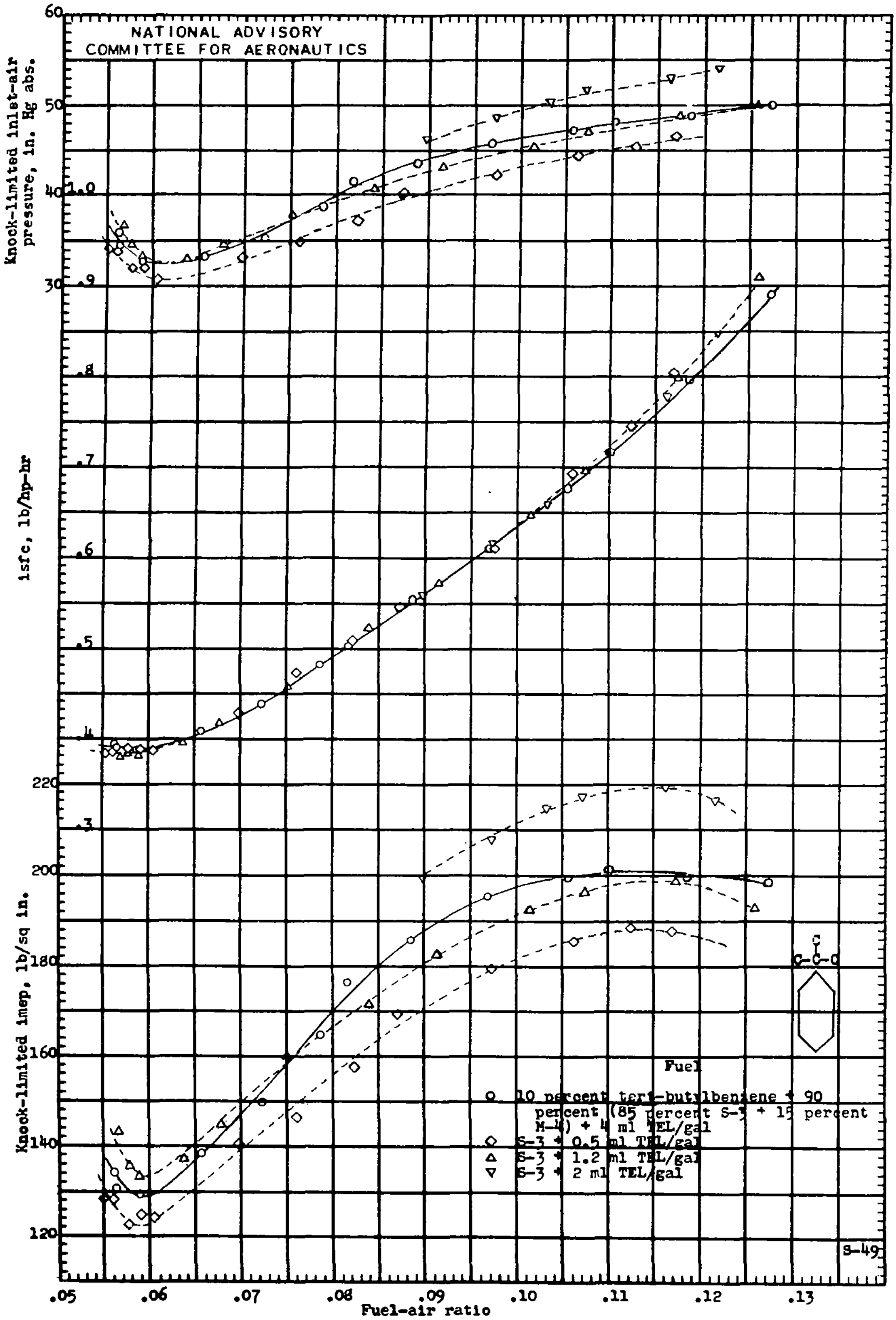
(b) 25 percent 1,3,5-trimethylbenzene plus 75 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per gallon.
Figure 2.



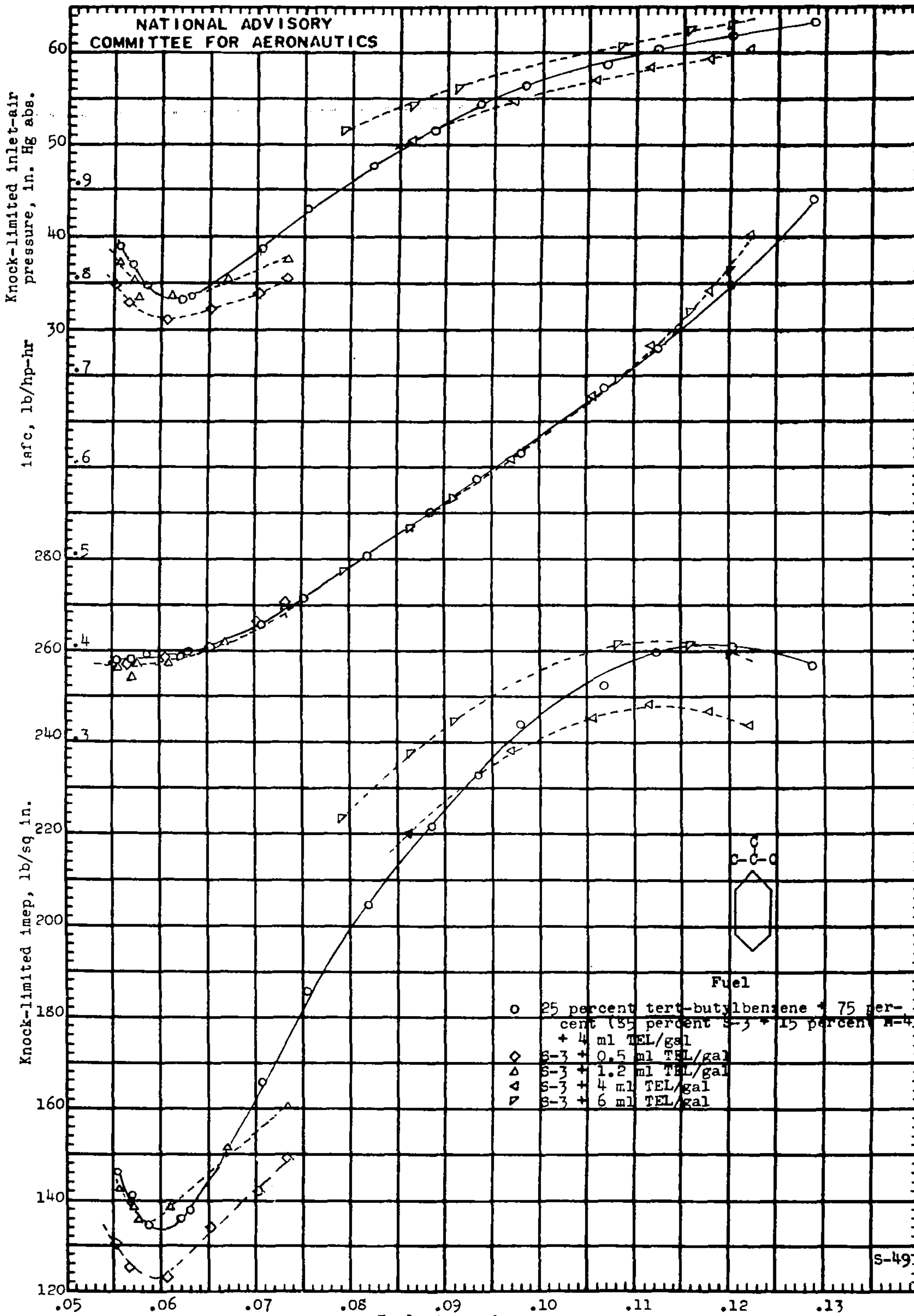
(c) 50 percent 1,3,5-trimethylbenzene plus 50 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per gallon.
Figure 2.



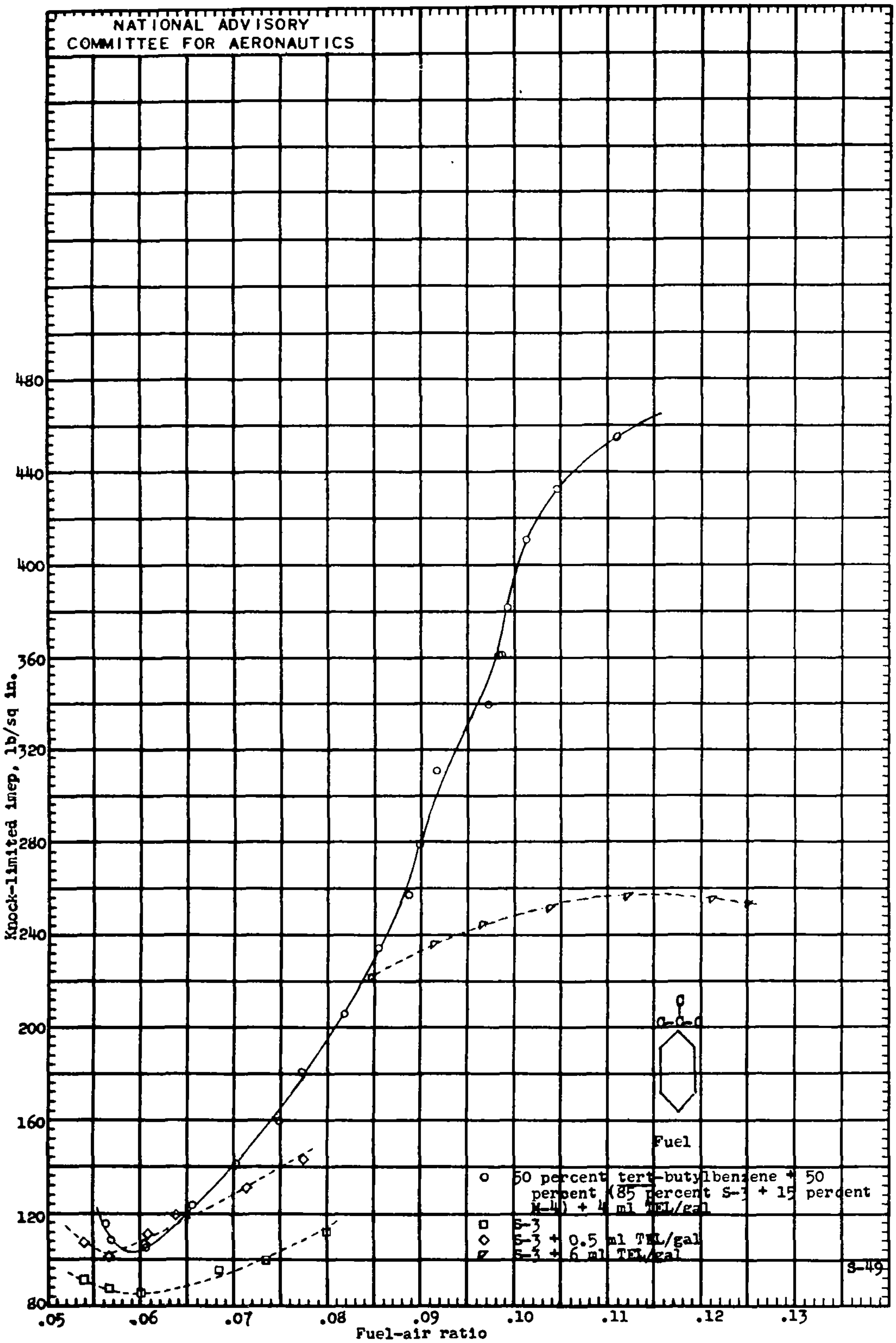
(c) Concluded.
Figure 2.-Concluded.



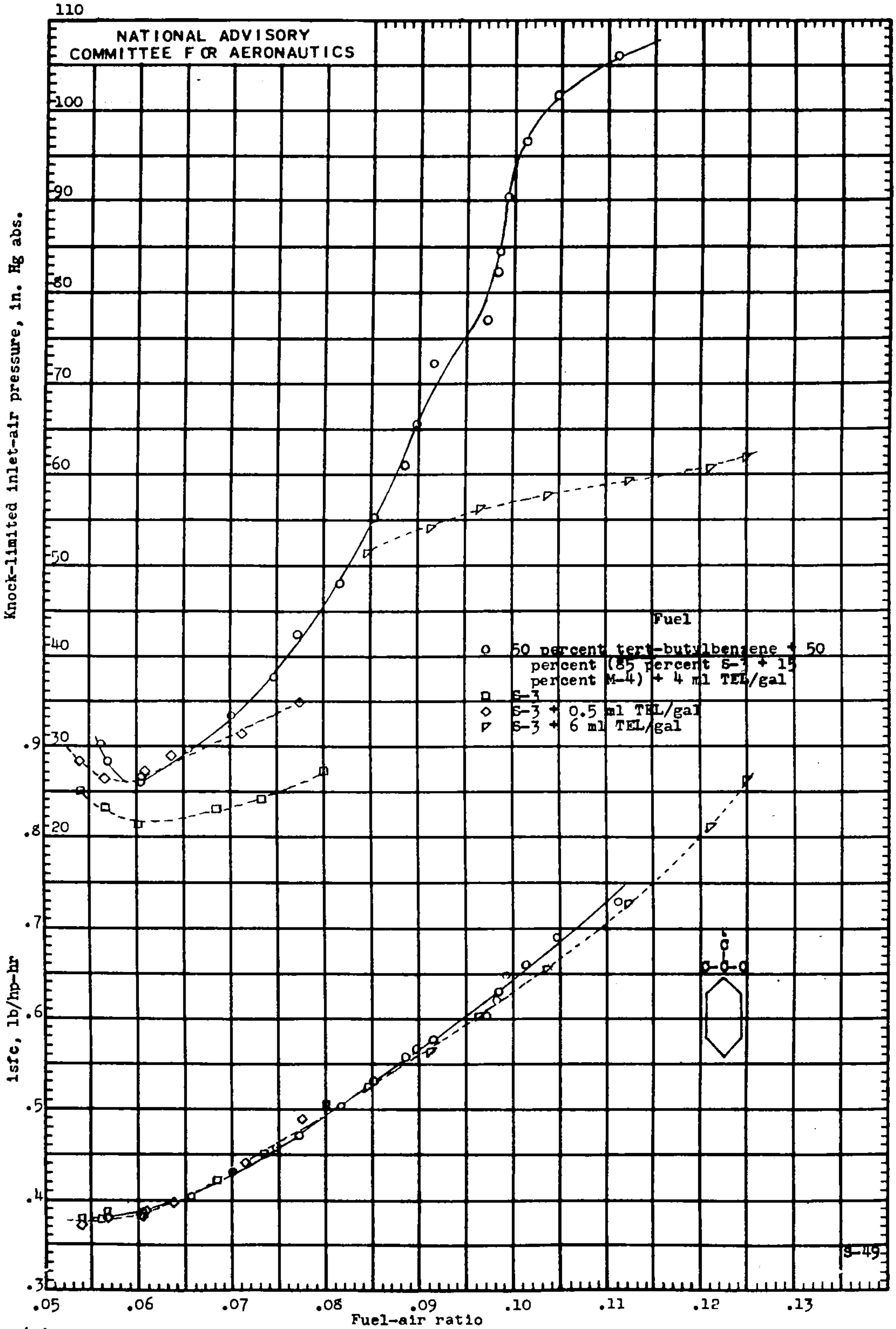
(a) 10 percent tert-butylbenzene plus 90 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per gallon.
Figure 3.



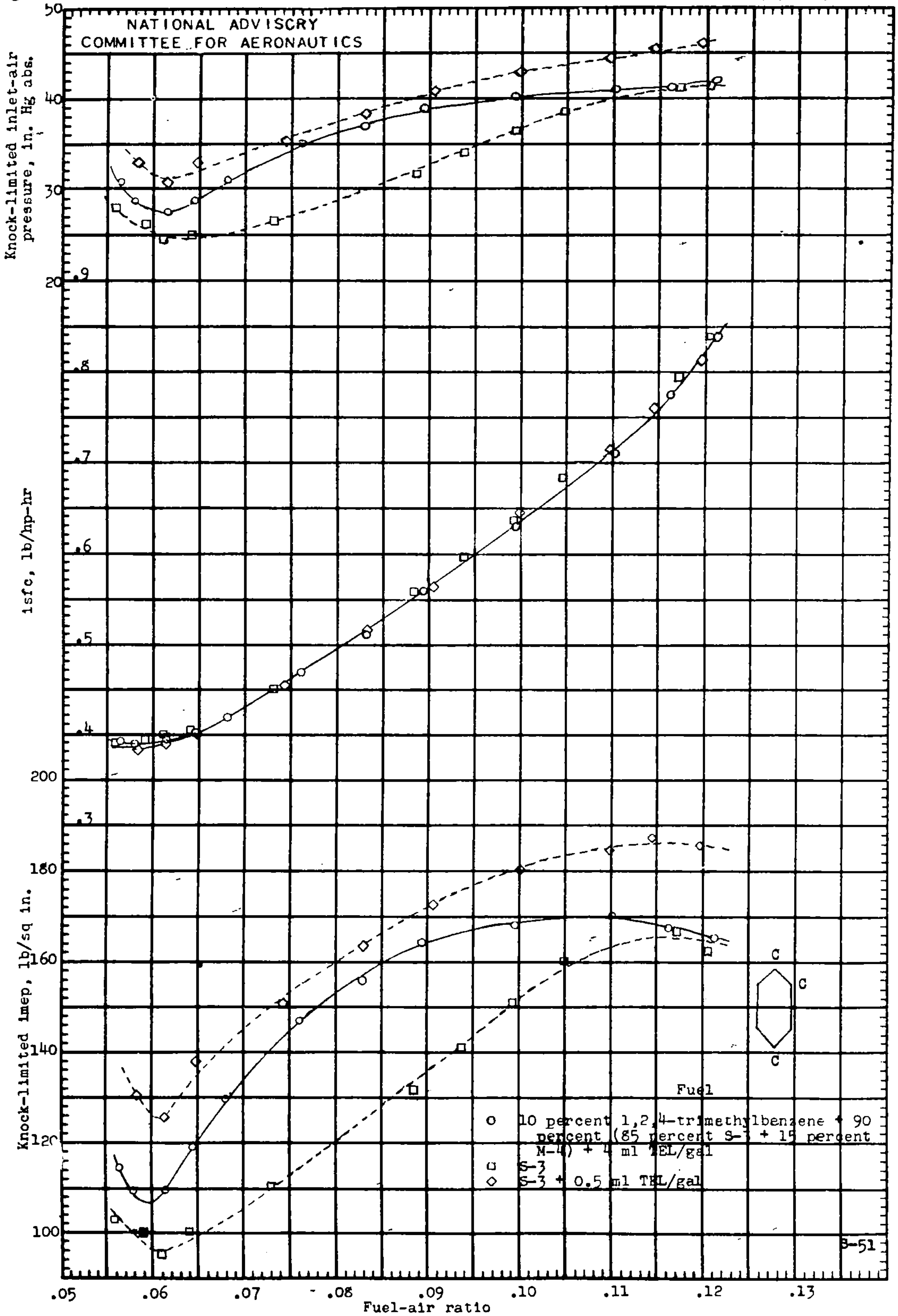
(b) 25 percent tert-butylbenzene plus 75 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per gallon.
Figure 3.



(c) 50 percent *tert*-butylbenzene plus 50 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per ballon.
Figure 3.

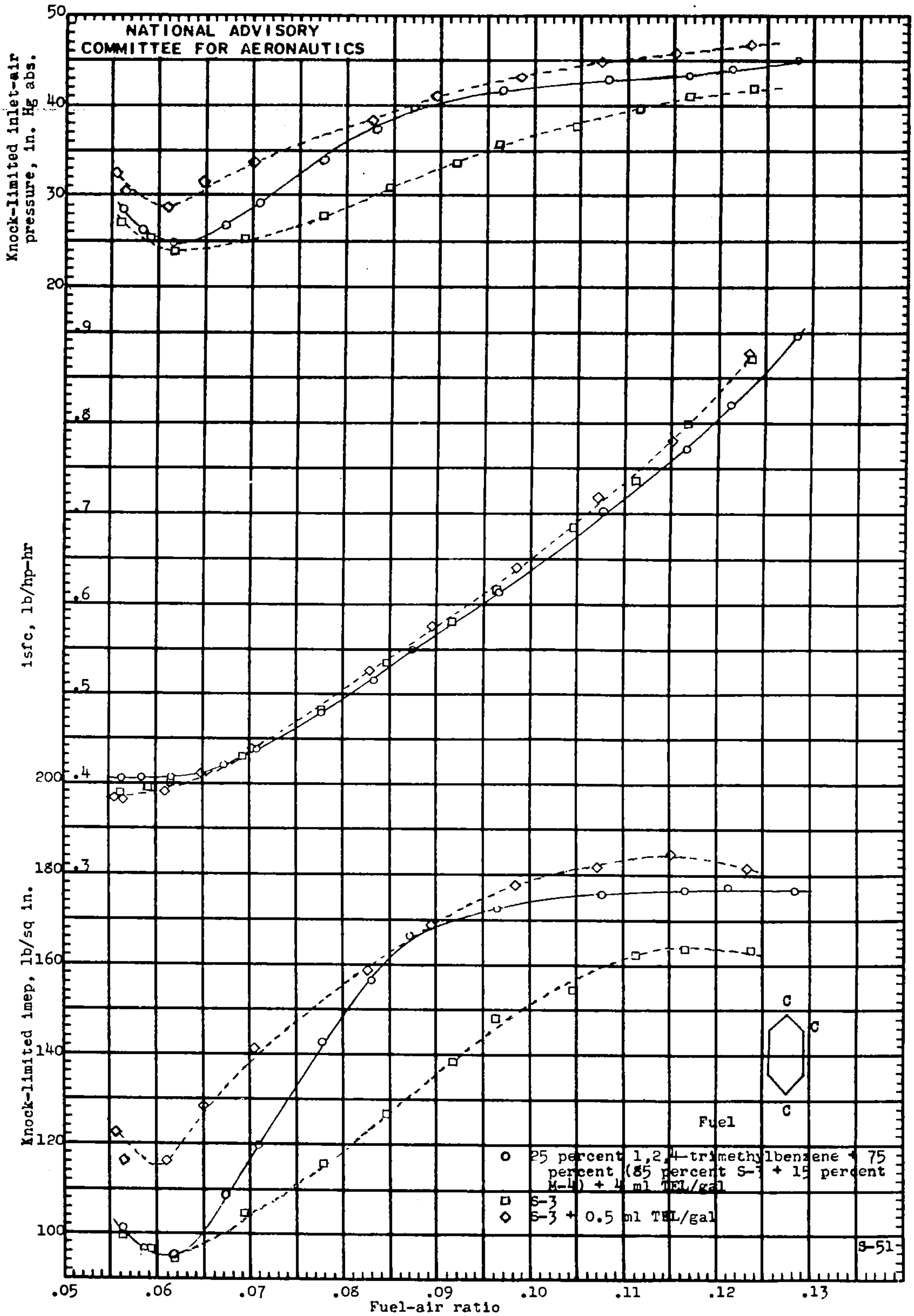


(c) Concluded.
Figure 3. - Concluded.

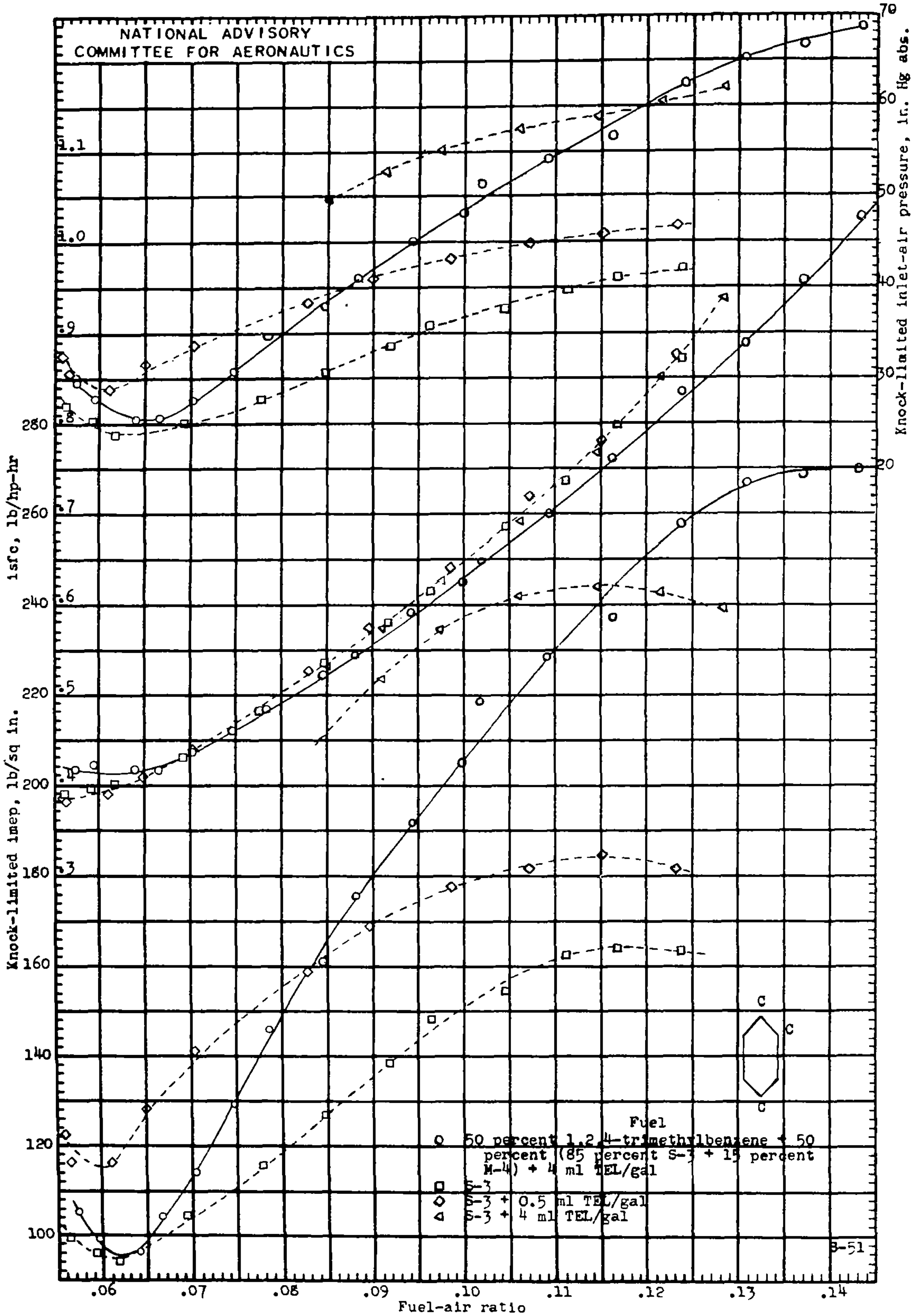


(a) 10 percent 1,2,4-trimethylbenzene plus 90 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per gallon.

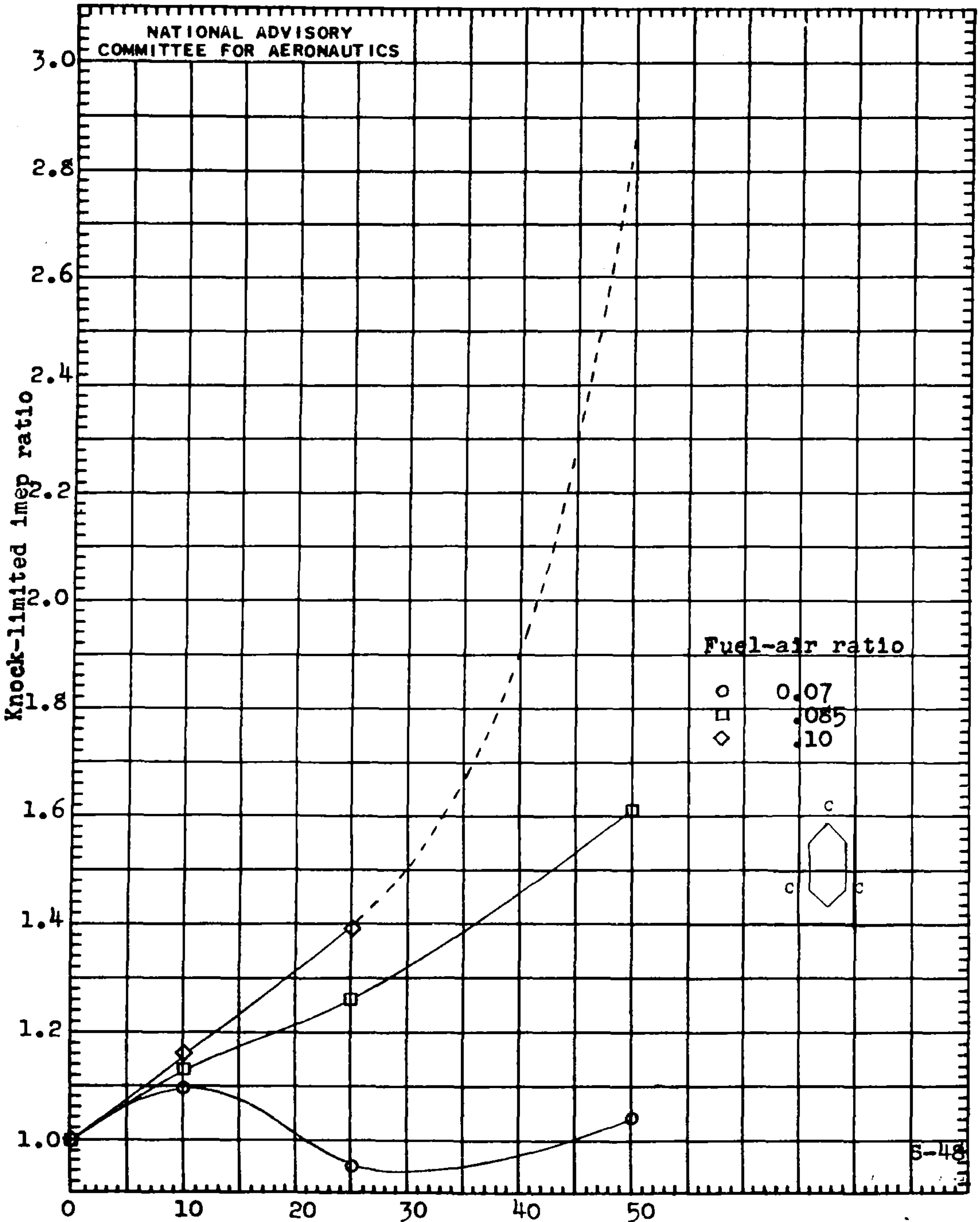
Figure 4. - Knock-limited performance of blends containing 1,2,4-trimethylbenzene in an F-4 engine.



(b) 25 percent 1,2,4-trimethylbenzene plus 75 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per gallon.
Figure 4.

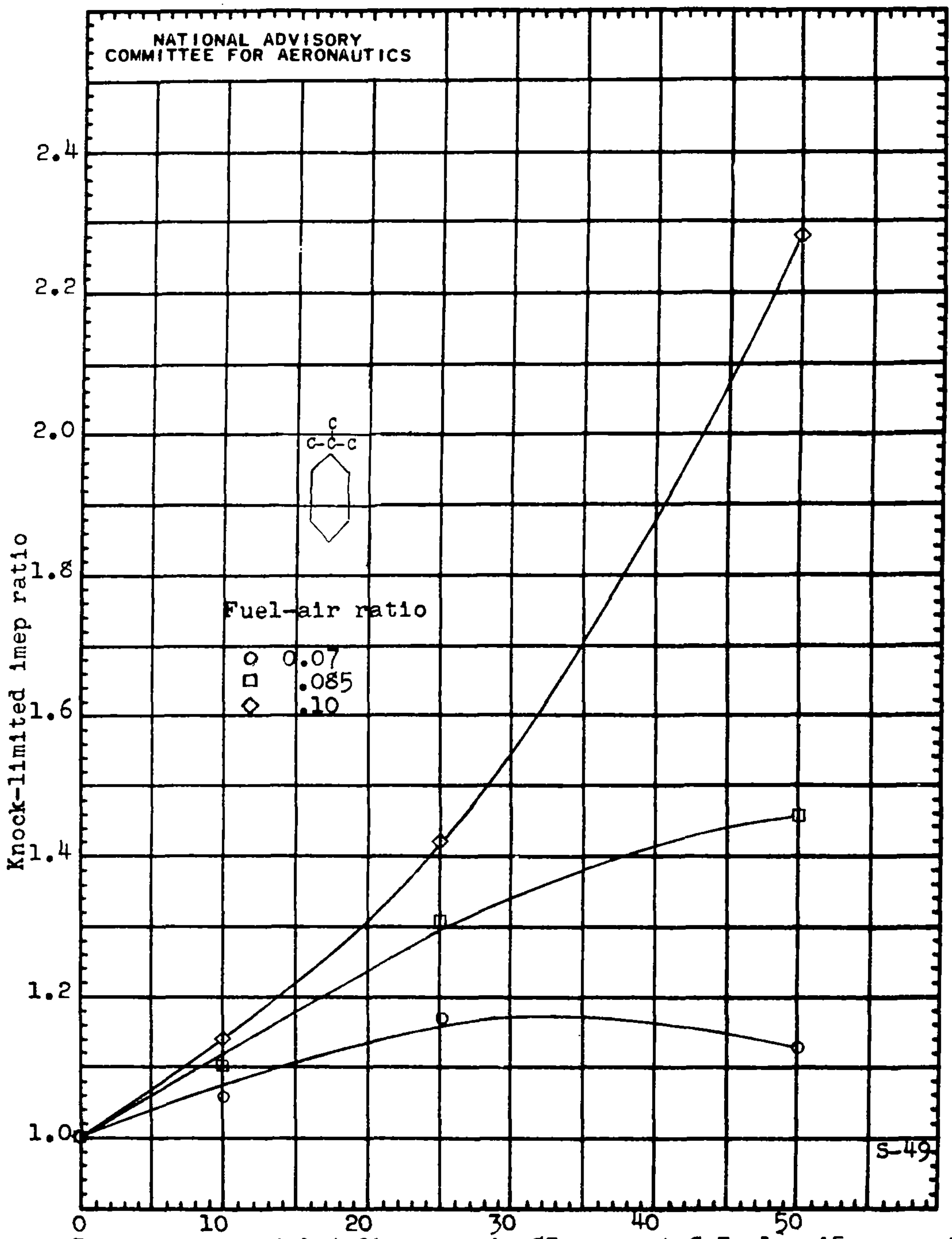


(c) 50 percent 1,2,4-trimethylbenzene plus 50 percent (85 percent S-3 plus 15 percent M-4) plus 4 ml TEL per gallon.
Figure 4.



Percentage 1,3,5-trimethylbenzene in 85 percent S-3 plus 15 percent M-4 base fuel

Figure 5. - The blending sensitivity of 1,3,5-trimethylbenzene in 85 percent S-3 plus 15 percent M-4. F-4 engine; final blends leaded to 4 ml TEL per gallon.



Percentage tert-butylbenzene in 85 percent S-3 plus 15 percent M-4 base fuel

Figure 6. - The blending sensitivity of tert-butylbenzene in 85 percent S-3 plus 15 percent M-4. F-4 engine; final blends leaded to 4 ml TEL per gallon.

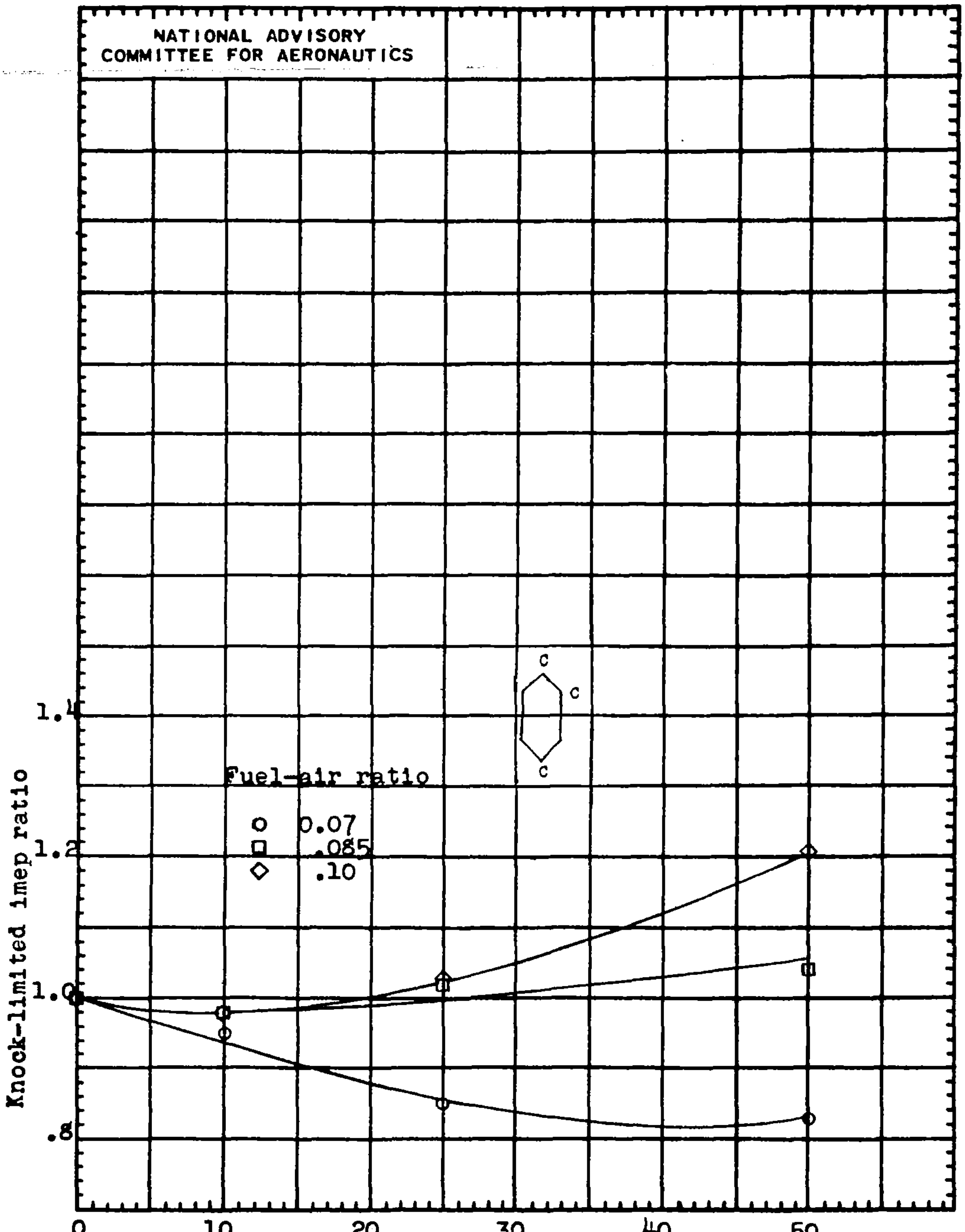
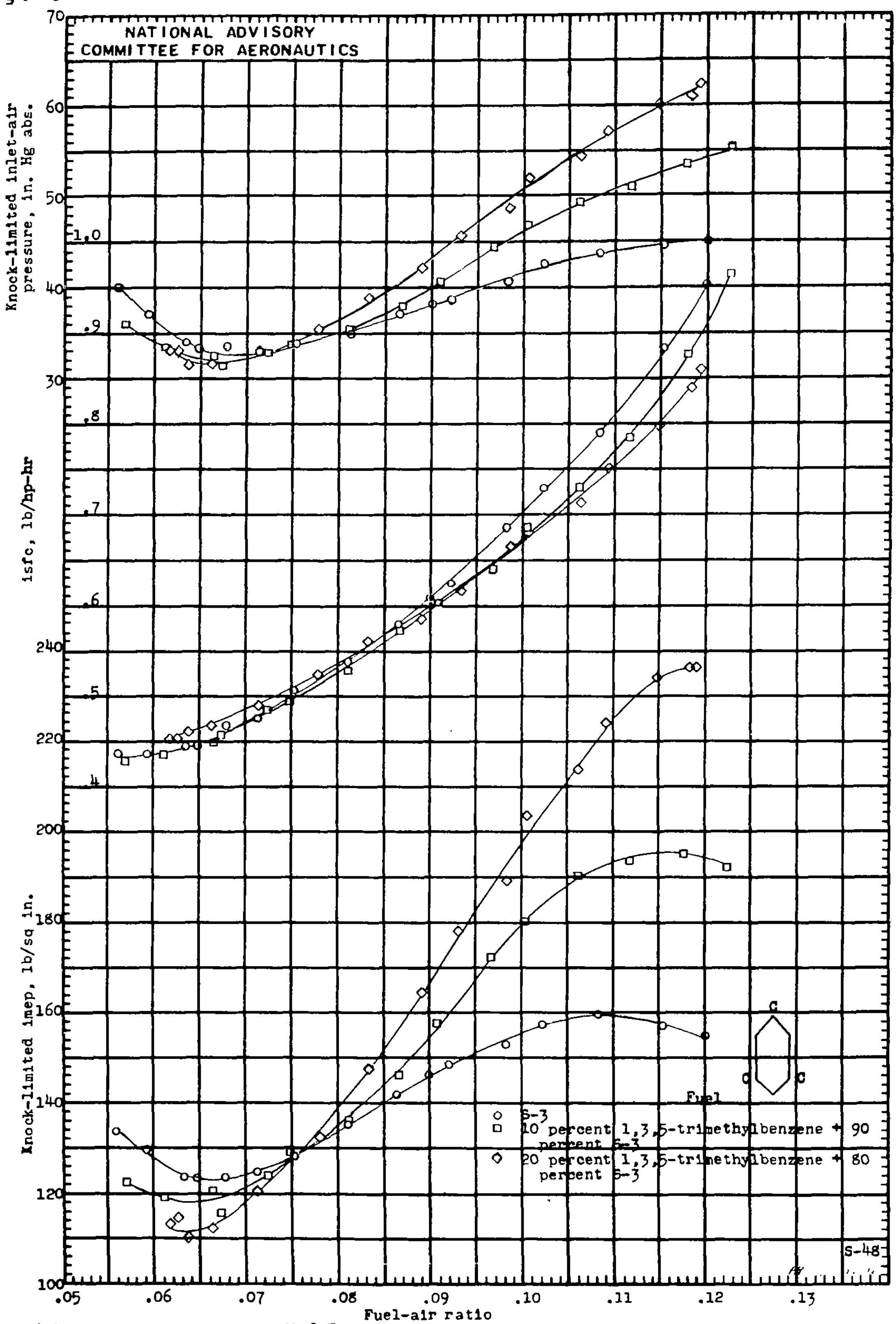


Figure 7. - The blending sensitivity of 1,2,4-trimethylbenzene in 85 percent S-3 plus 15 percent M-4. F-4 engine; final blends leaded to 4 ml TEL per gallon.



(a) Inlet-air temperature, 250° F.

Figure 8. - Knock-limited performance of blends of 1,3,5-trimethylbenzene and S-3 reference fuel. 17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

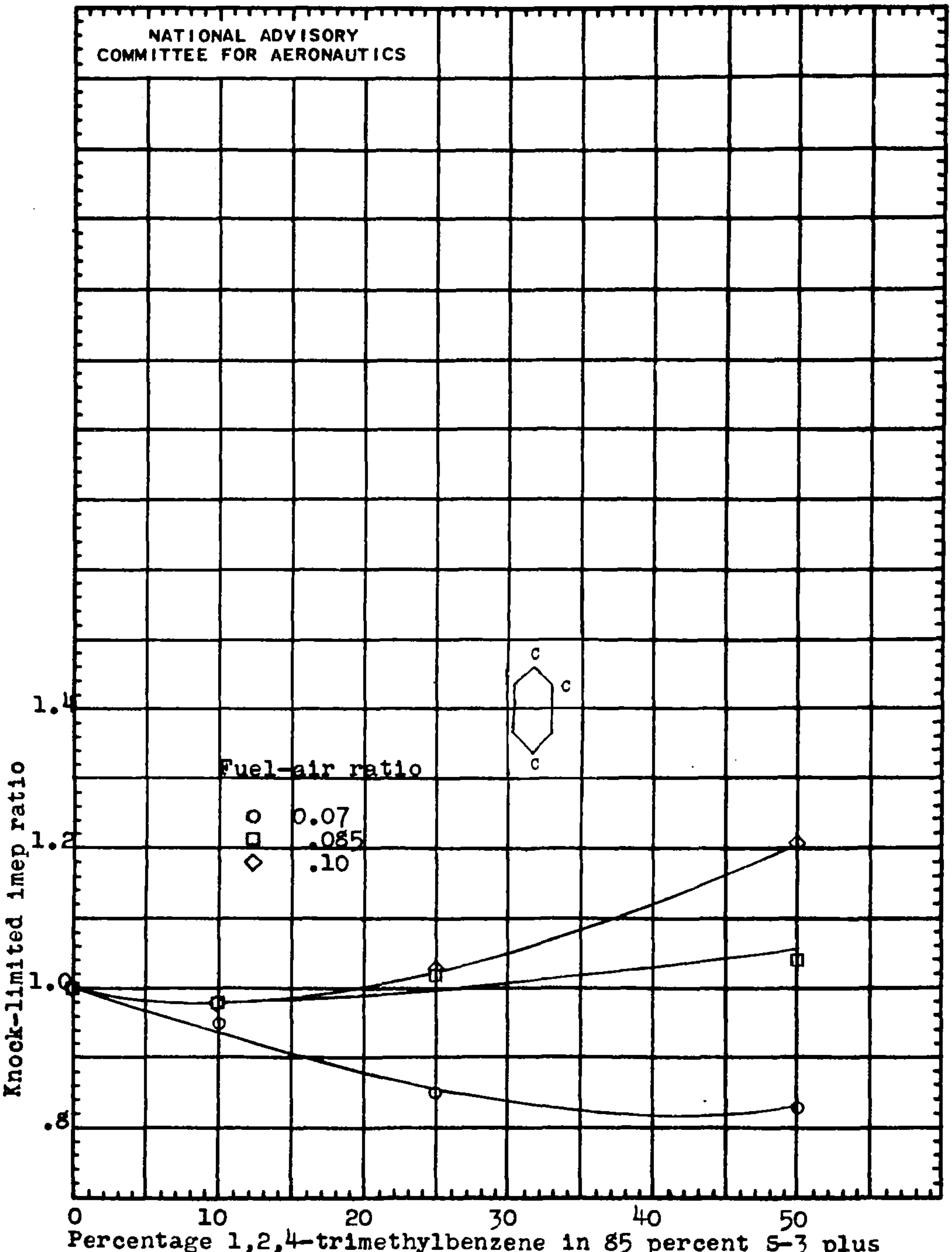
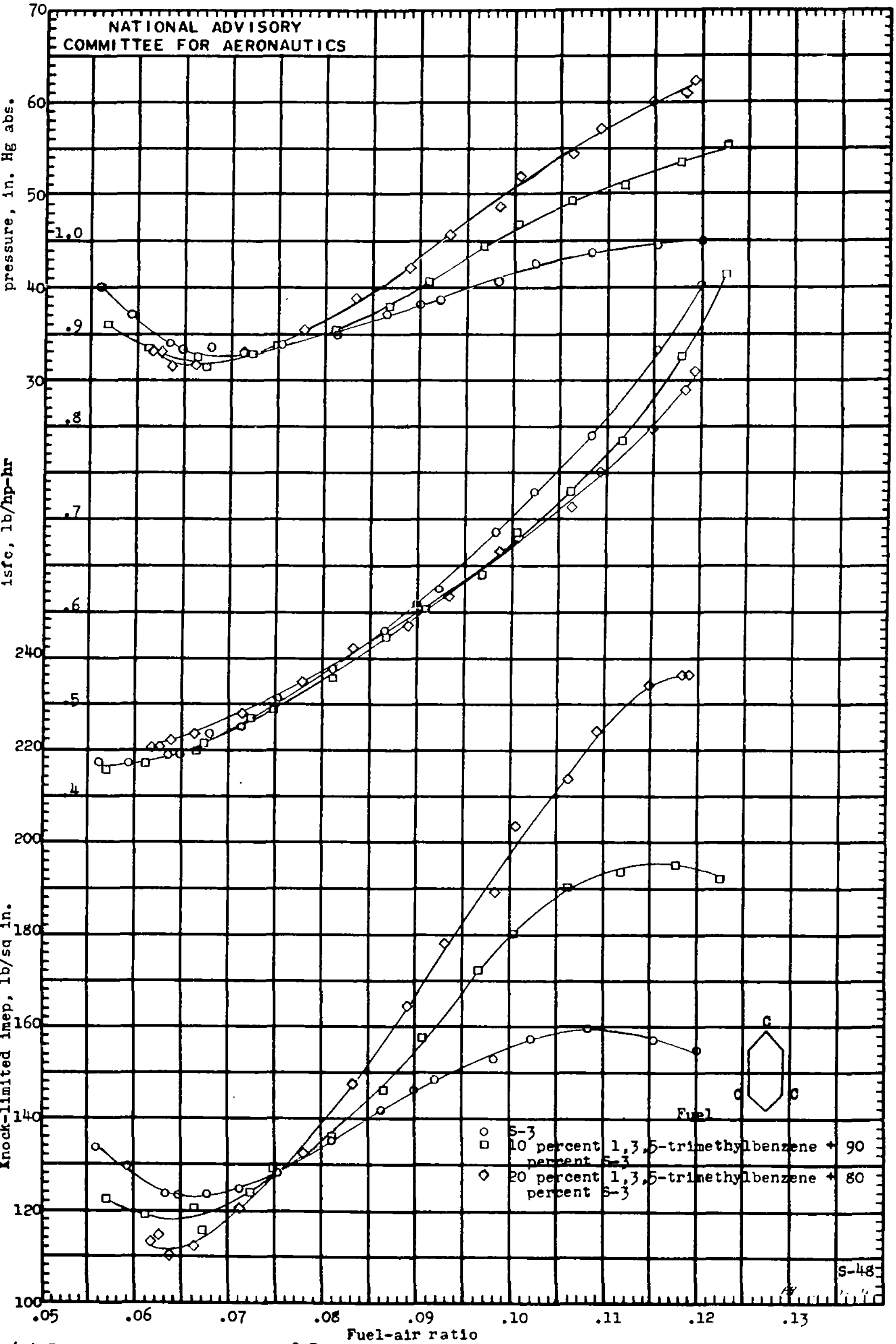
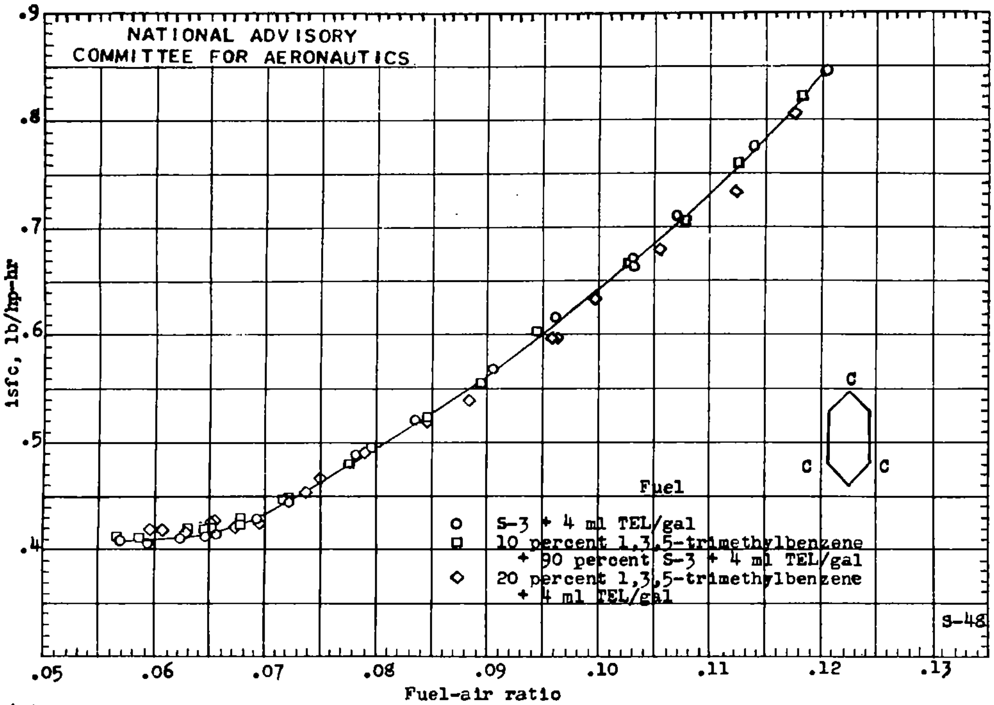


Figure 7. - The blending sensitivity of 1,2,4-trimethylbenzene in 85 percent S-3 plus 15 percent M-4. F-4 engine; final blends leaded to 4 ml TEL per gallon.

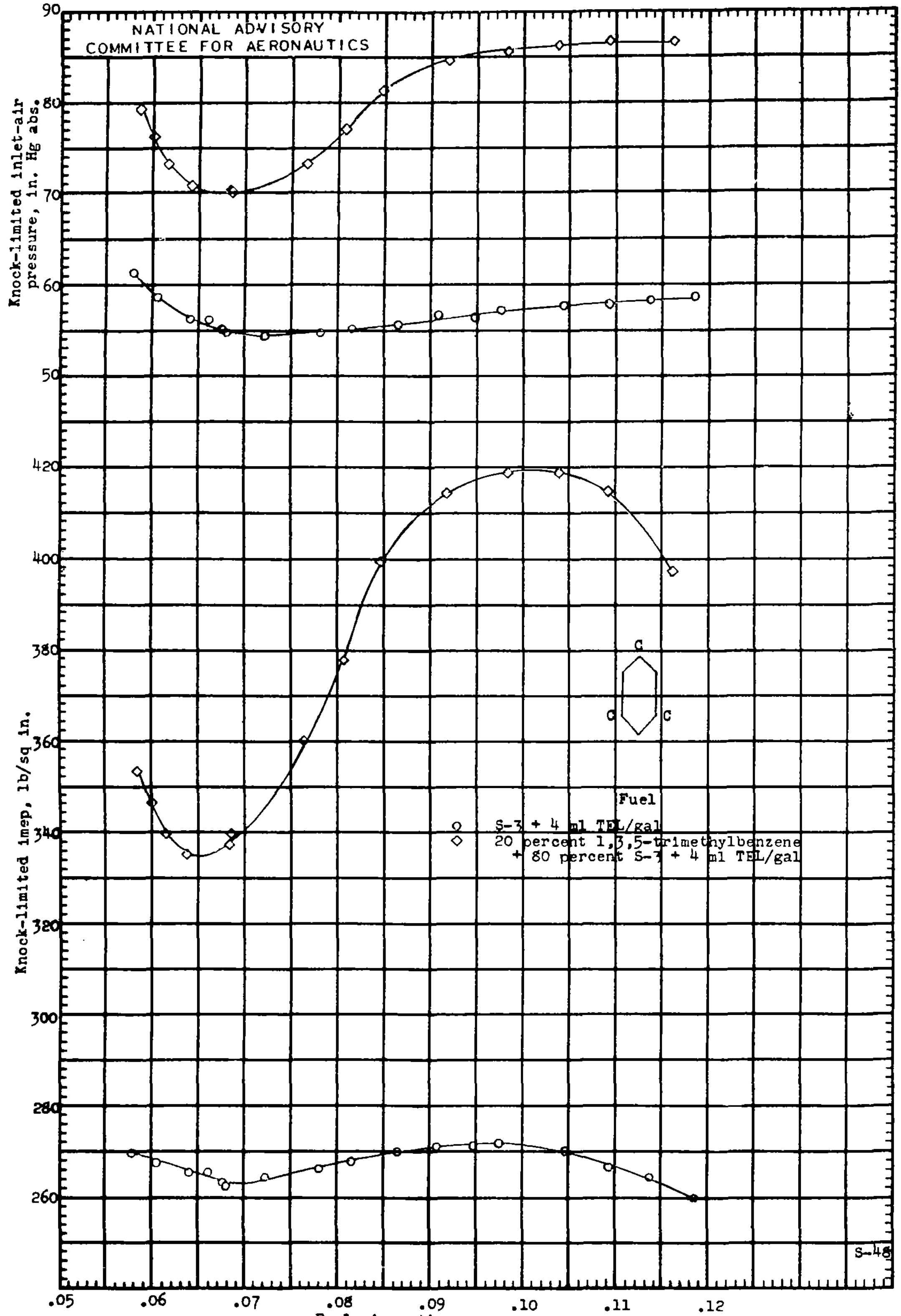


(a) Inlet-air temperature, 250° F.

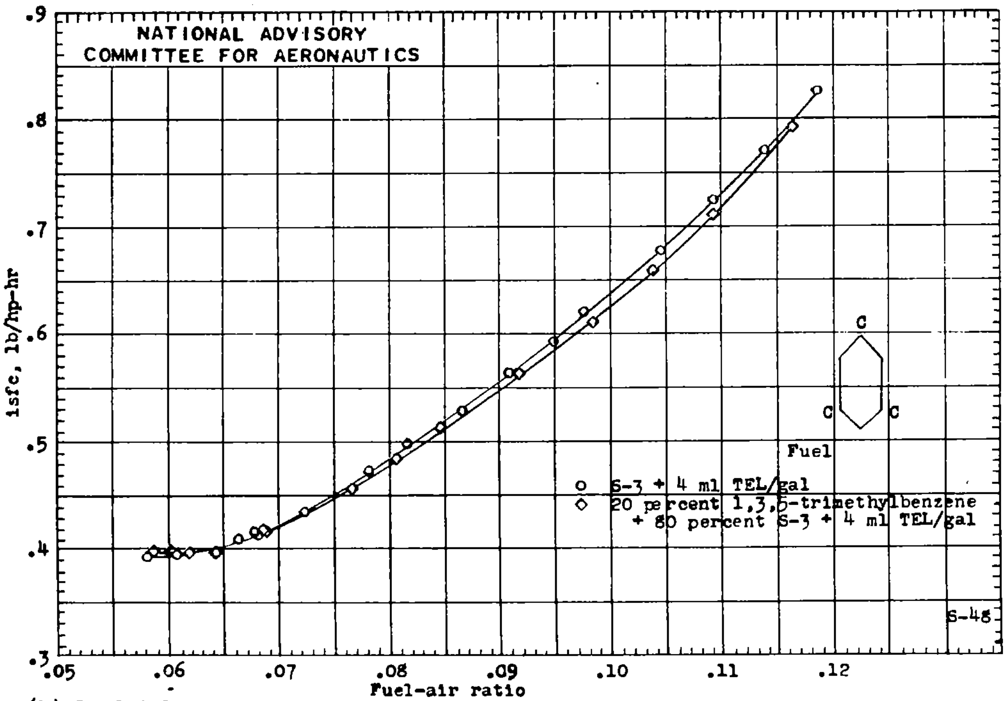
Figure 8. - Knock-limited performance of blends of 1,3,5-trimethylbenzene and S-3 reference fuel. 17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.



(a) Concluded.
Figure 9. - Continued.



(b) Inlet-air temperature, 100° F.
Figure 9. - Continued.



(b) Concluded.
Figure 9. - Concluded.

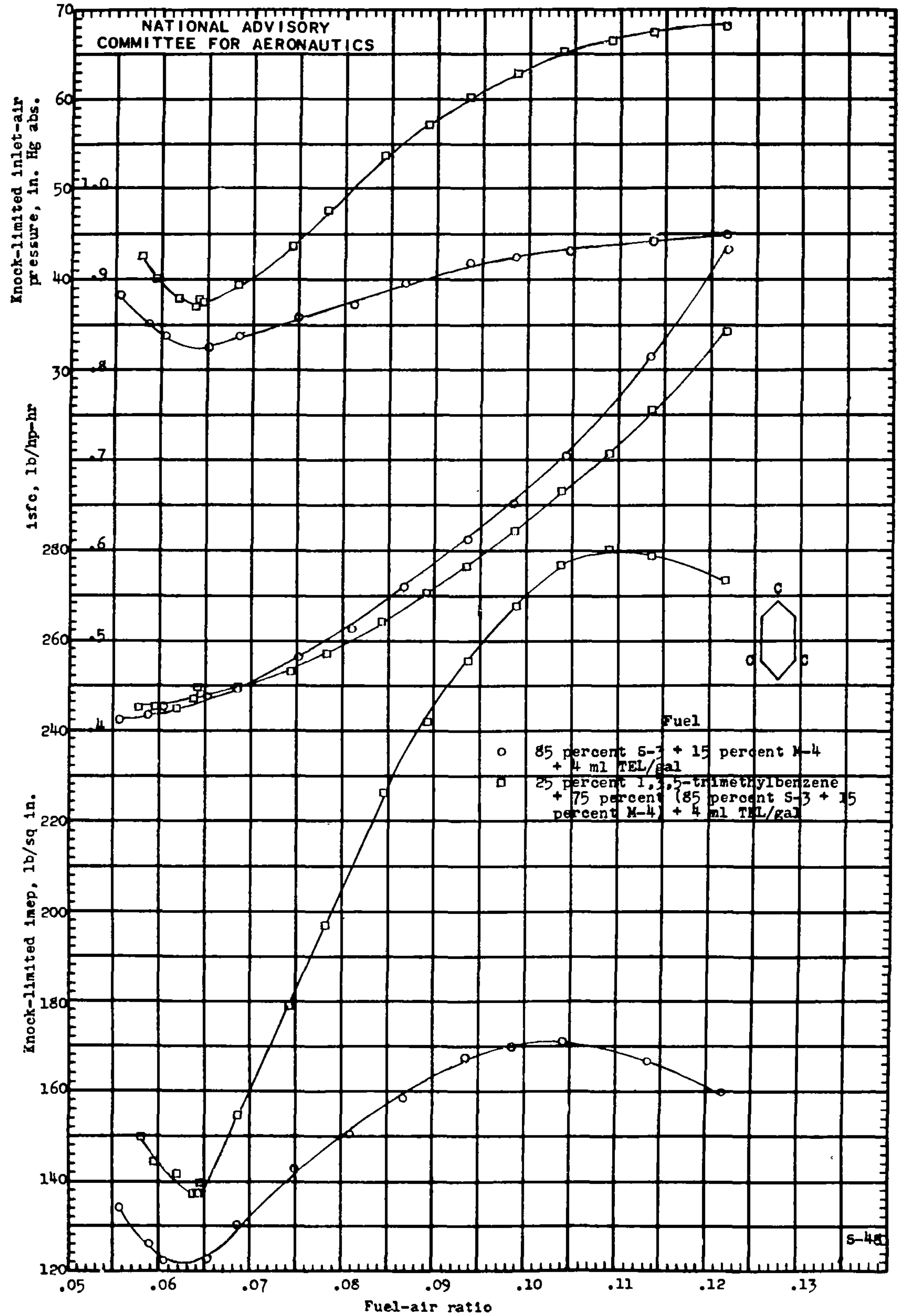
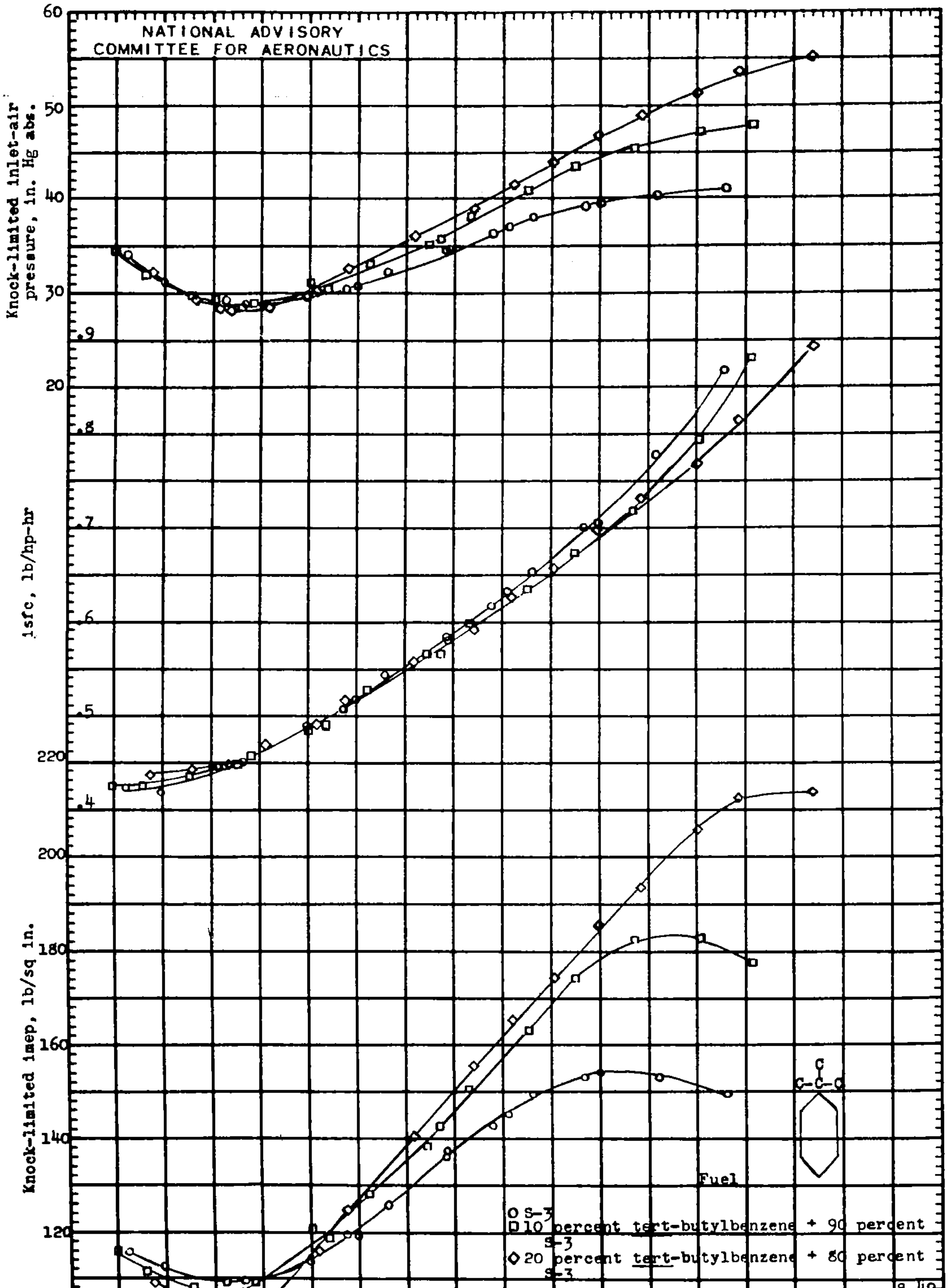
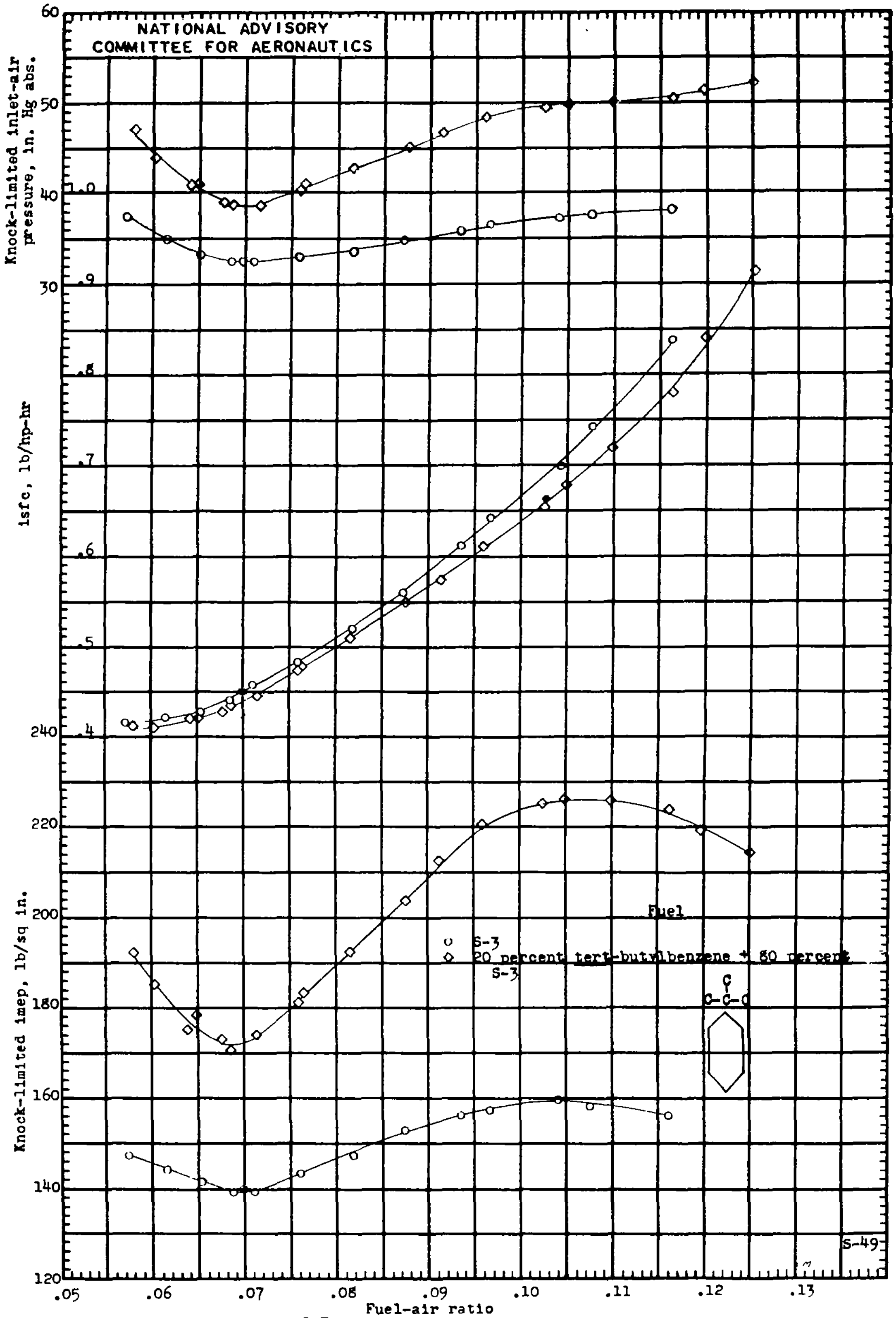


Figure 10. - Knock-limited performance of blends of 1,3,5-trimethylbenzene and 85 percent S-3 plus 15 percent M-4 plus 4 ml TEL per gallon. 17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F; inlet-air temperature, 250° F.

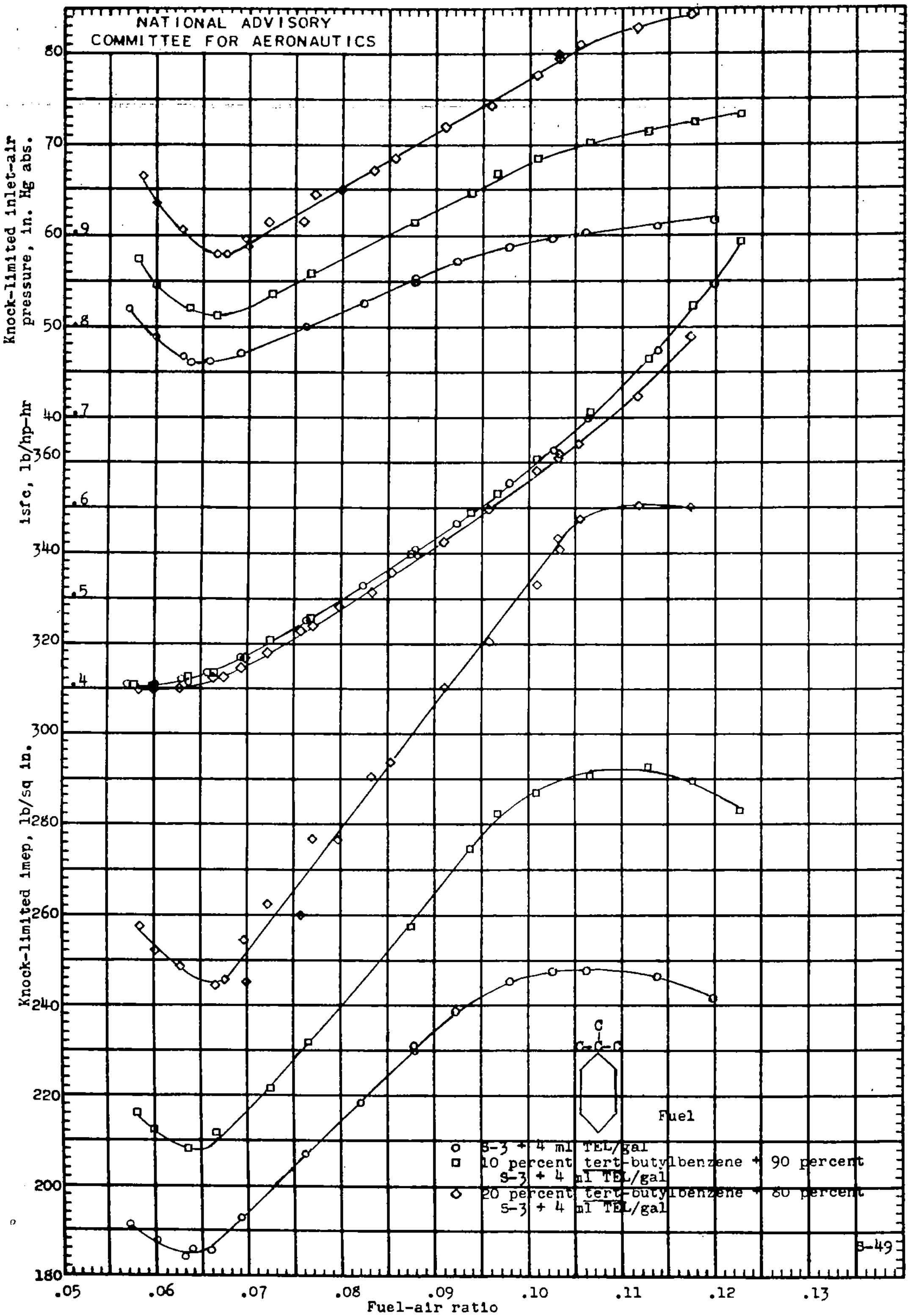


(a) Inlet-air temperature, 250° F.

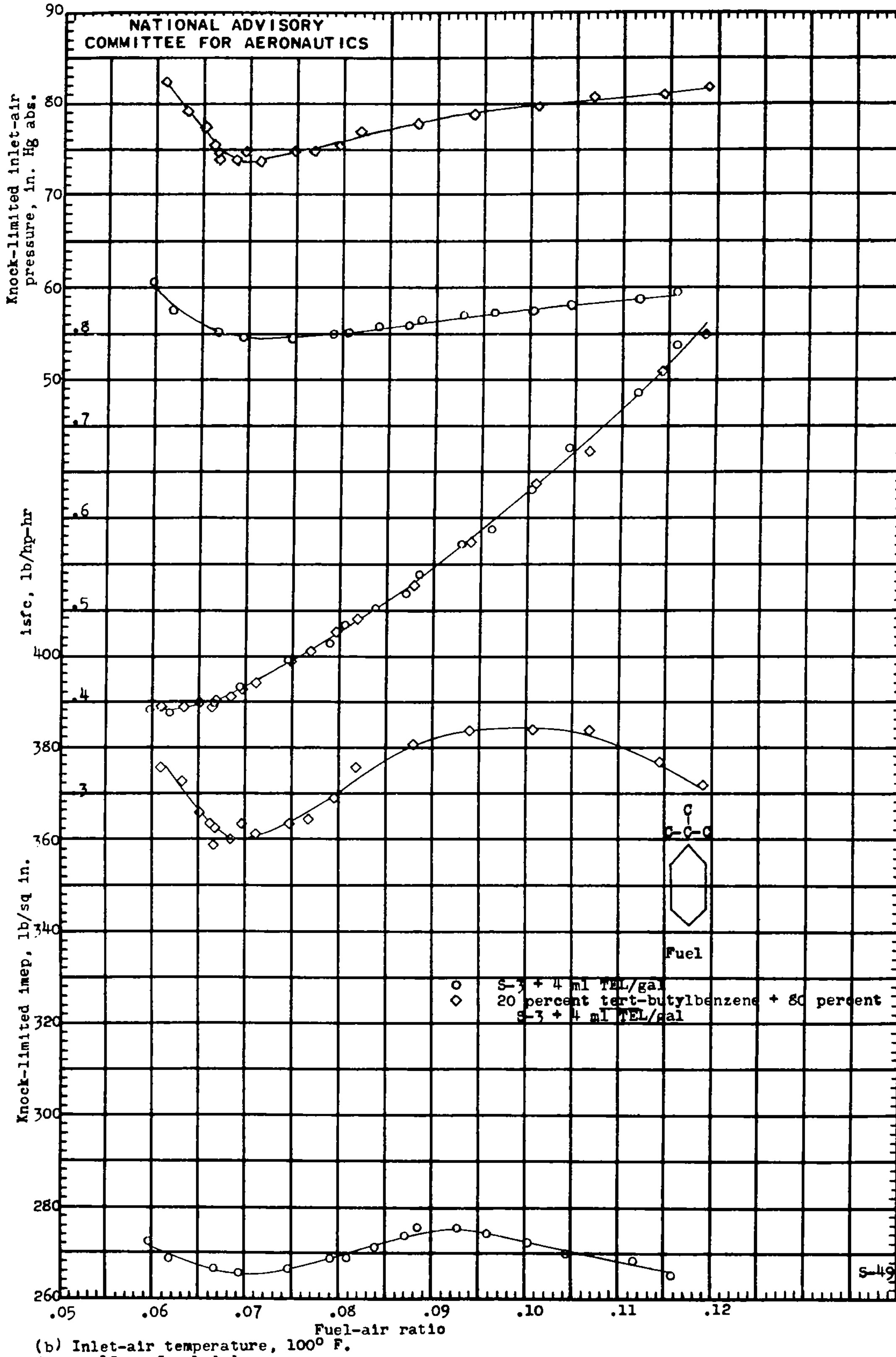
Figure 11. - Knock-limited performance of blends of *tert*-butylbenzene and S-3 reference fuel. 17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.



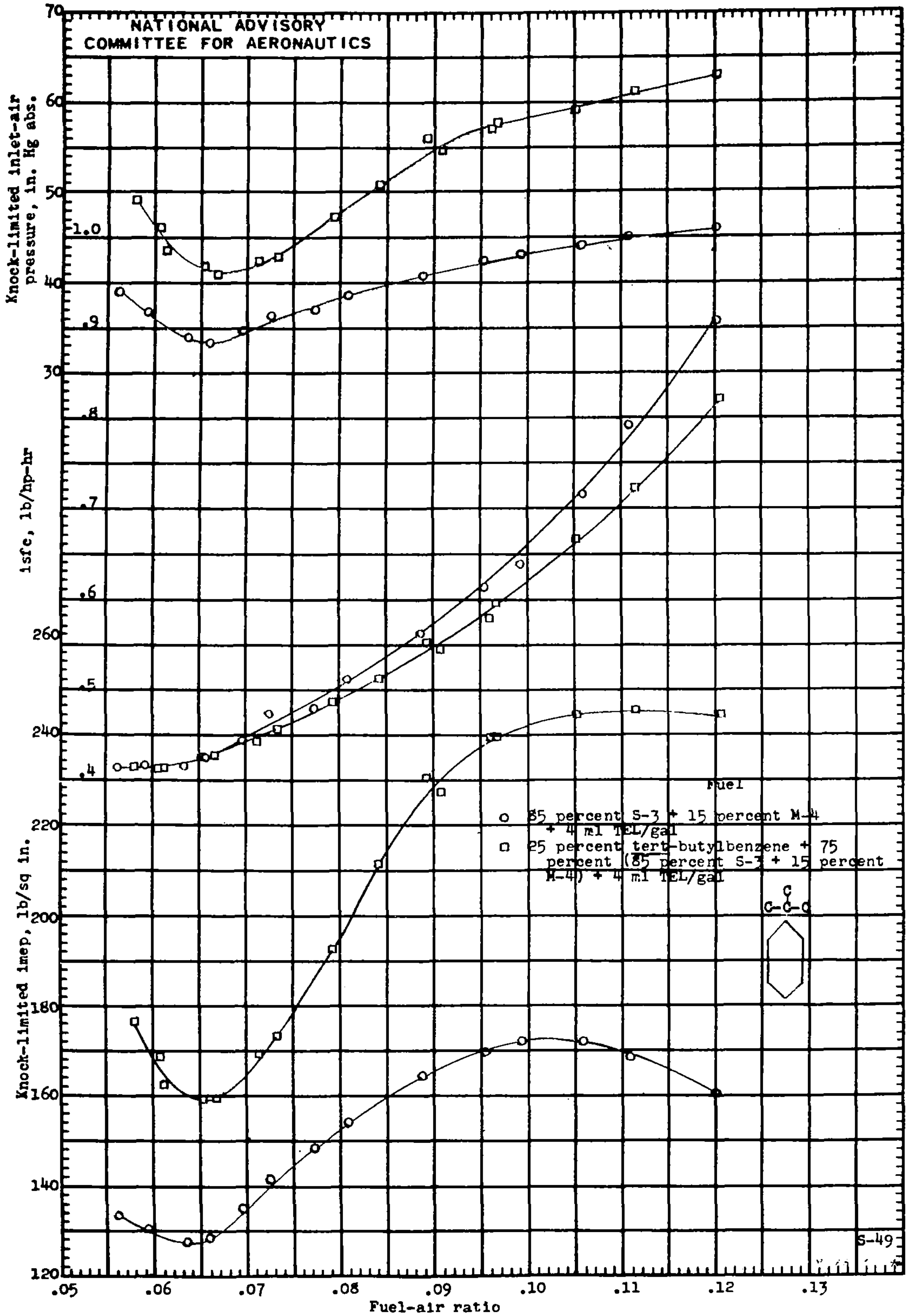
(b) Inlet-air temperature, 100° F.
Figure 11. - Concluded.



(a) Inlet-air temperature, 250° F.
Figure 12. - Knock-limited performance of blends of tert-butylbenzene and S-3 reference fuel plus 4 ml TEL per gallon. 17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

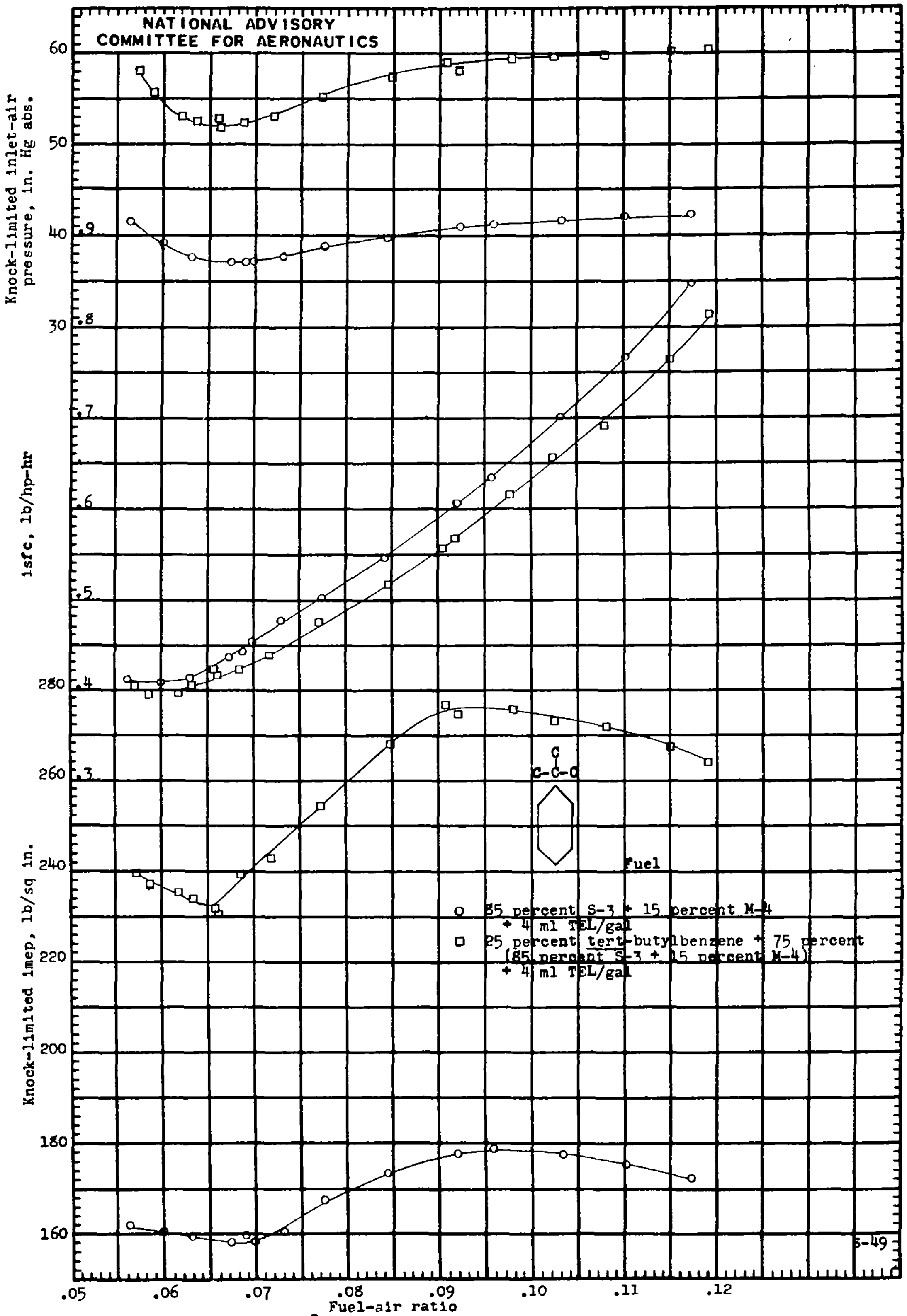


(b) Inlet-air temperature, 100° F.
Figure 12. - Concluded.

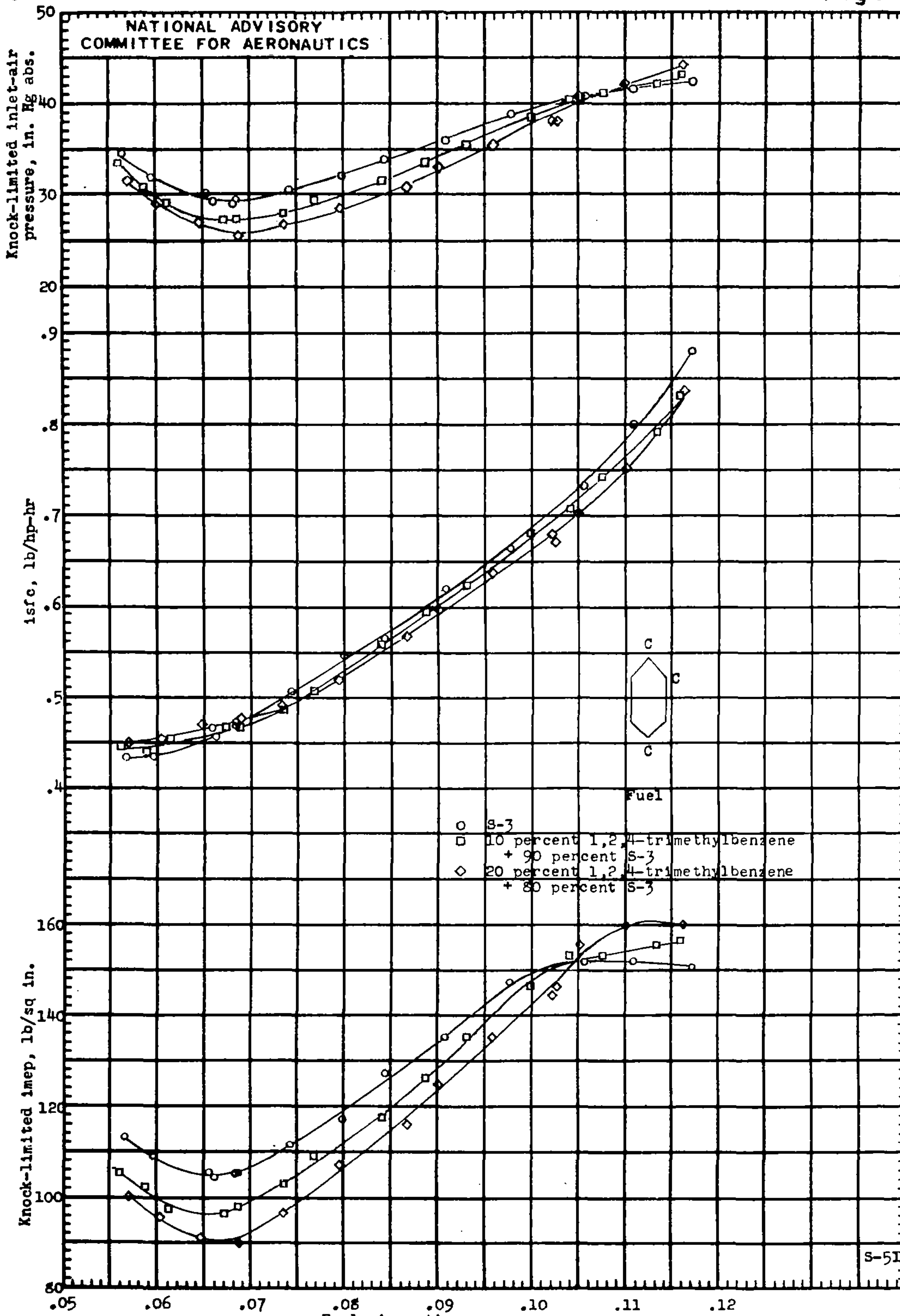


(a) Inlet-air temperature, 250° F.

Figure 13. - Knock-limited performance of blends of tert-butylbenzene and 85 percent S-3 plus 15 percent M-4 plus 4 ml TEL per gallon. 17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

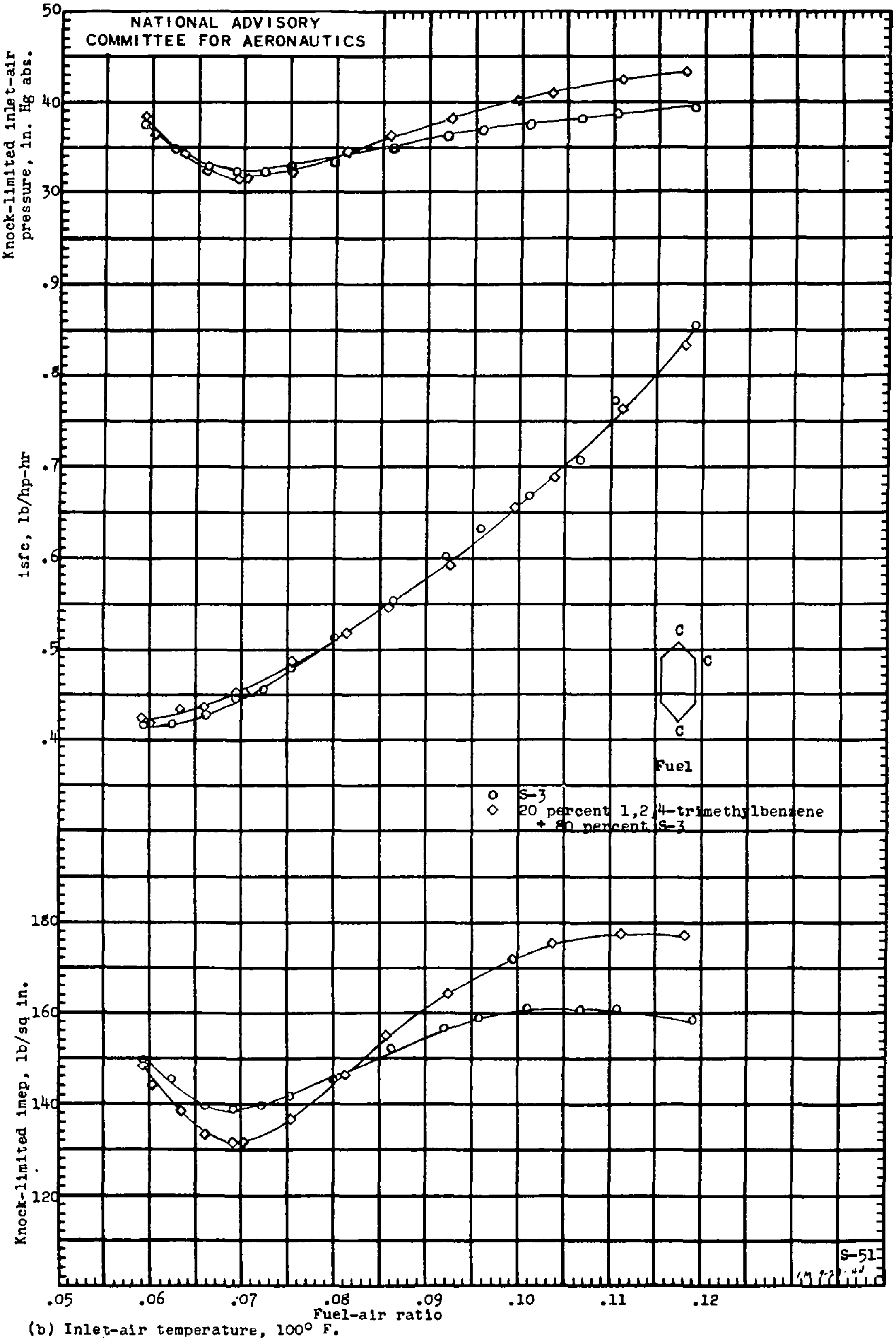


(b) Inlet-air temperature, 100° F.
Figure 13. - Concluded.

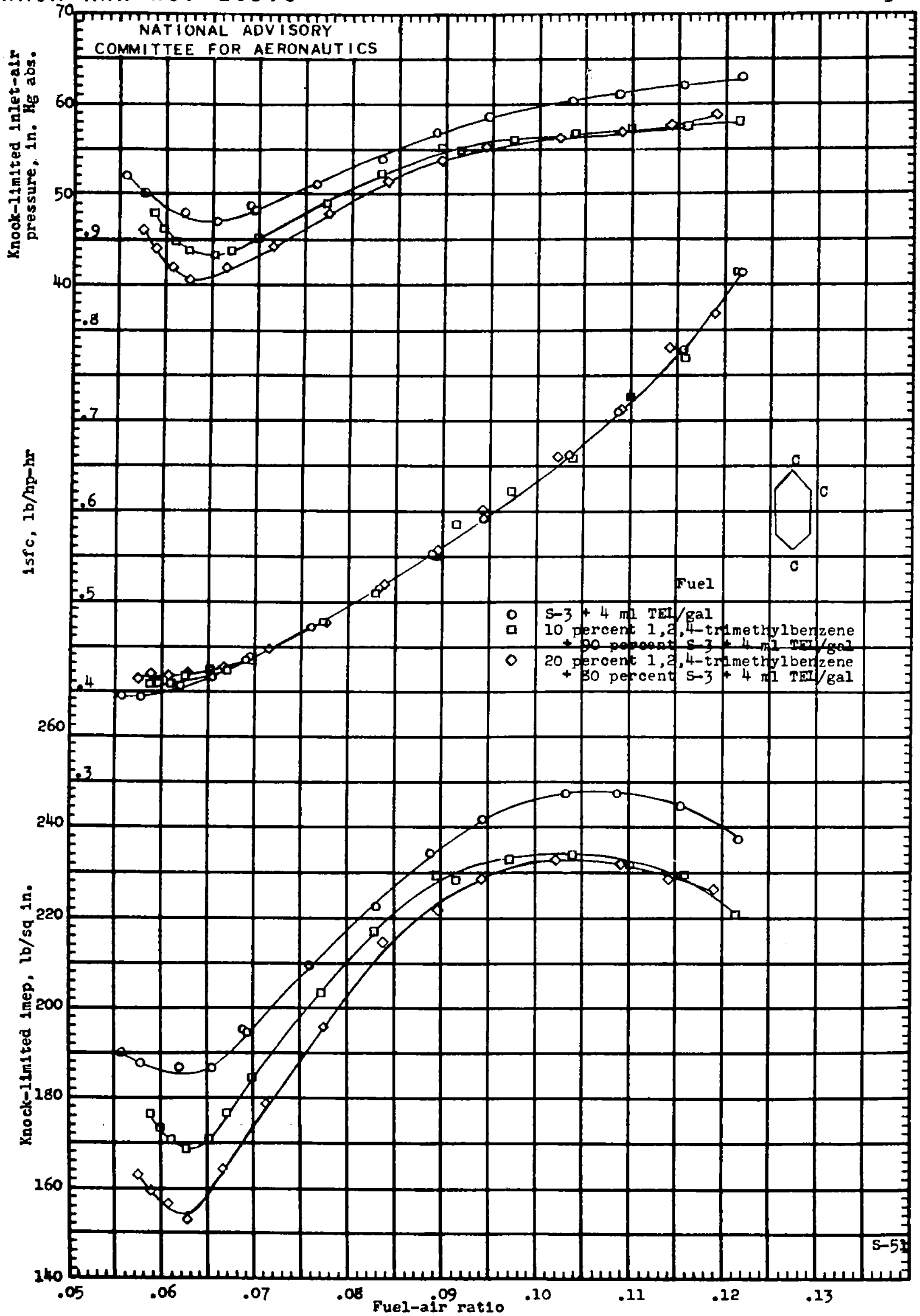


(a) Inlet-air temperature, 250° F.

Figure 14. - Knock-limited performance of blends of 1,2,4-trimethylbenzene and S-3 reference fuel. 17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

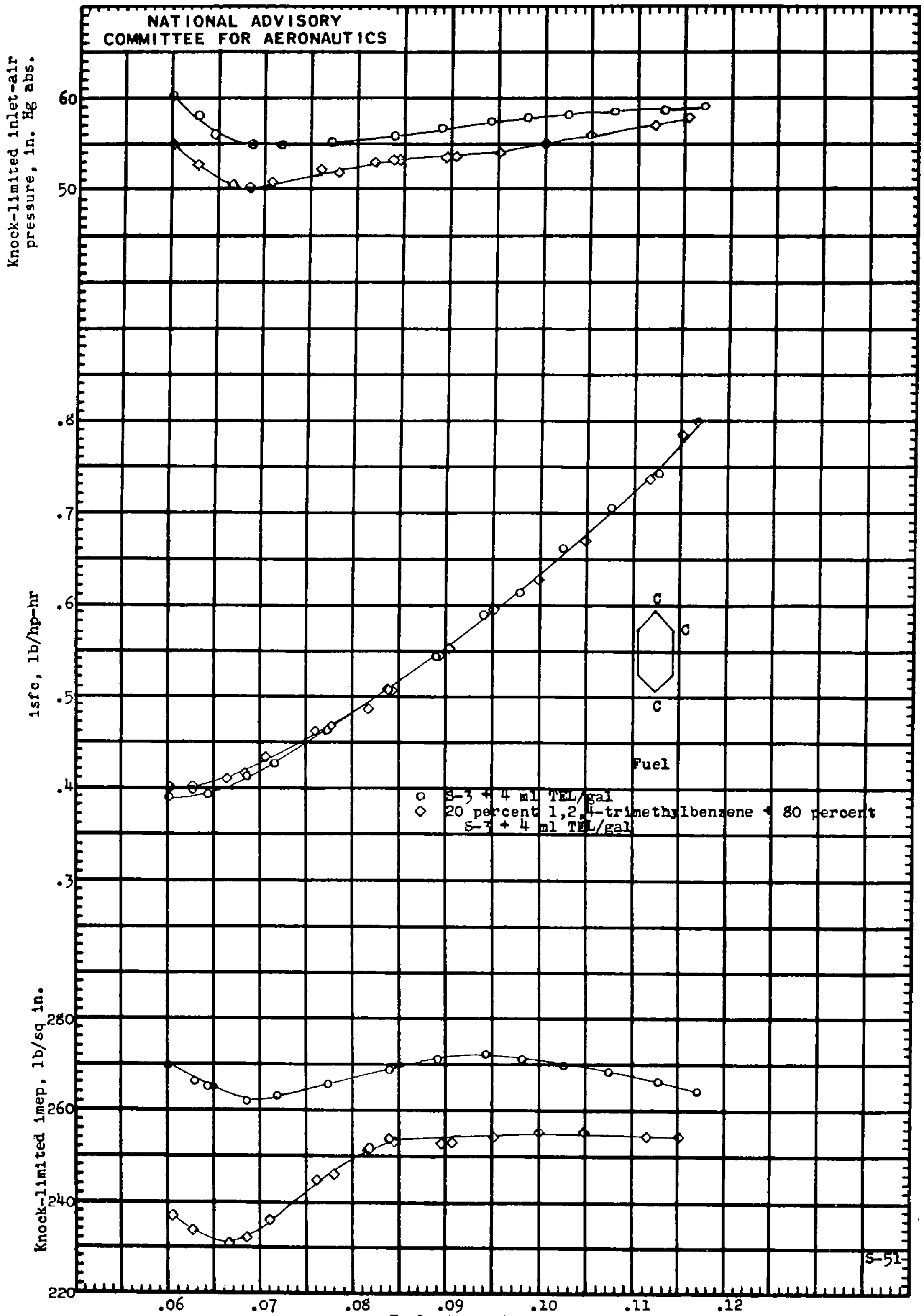


(b) Inlet-air temperature, 100° F.
Figure 14. - Concluded.

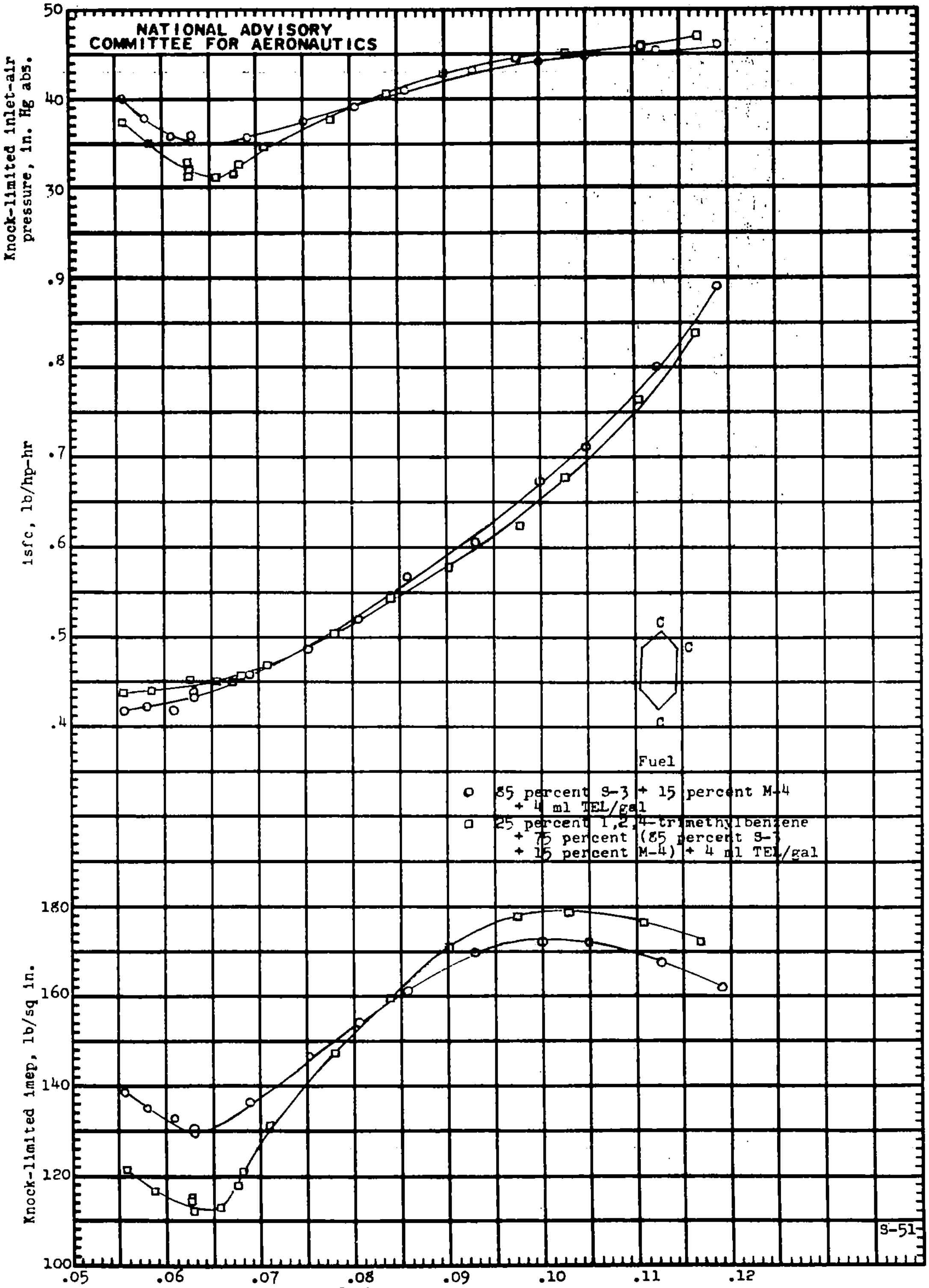


(a) Inlet-air temperature, 250° F.

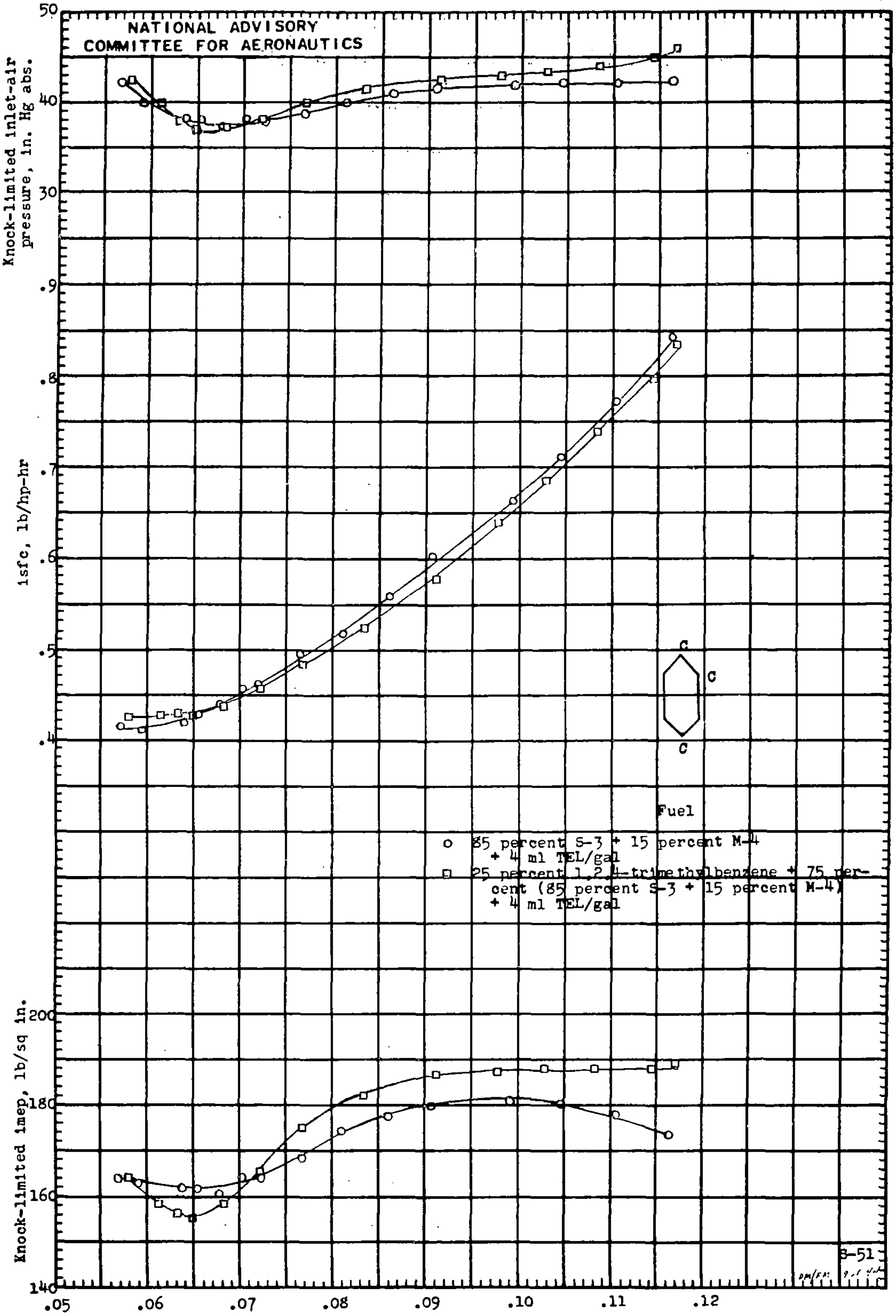
Figure 15. - Knock-limited performance of blends of 1,2,4-trimethylbenzene and S-3 reference fuel plus 4 ml TEL per gallon. 17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm: spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.



(b) Inlet-air temperature, 100° F.
Figure 15. - Concluded.



(a) Inlet-air temperature, 250° F.
Figure 16. - Knock-limited performance of blends of 1,2,4-trimethylbenzene and 85 percent S-3 plus 15 percent M-4 plus 4 ml TEL per gallon. 17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.



(b) Inlet-air temperature, 100° F.
Figure 16. - Concluded.

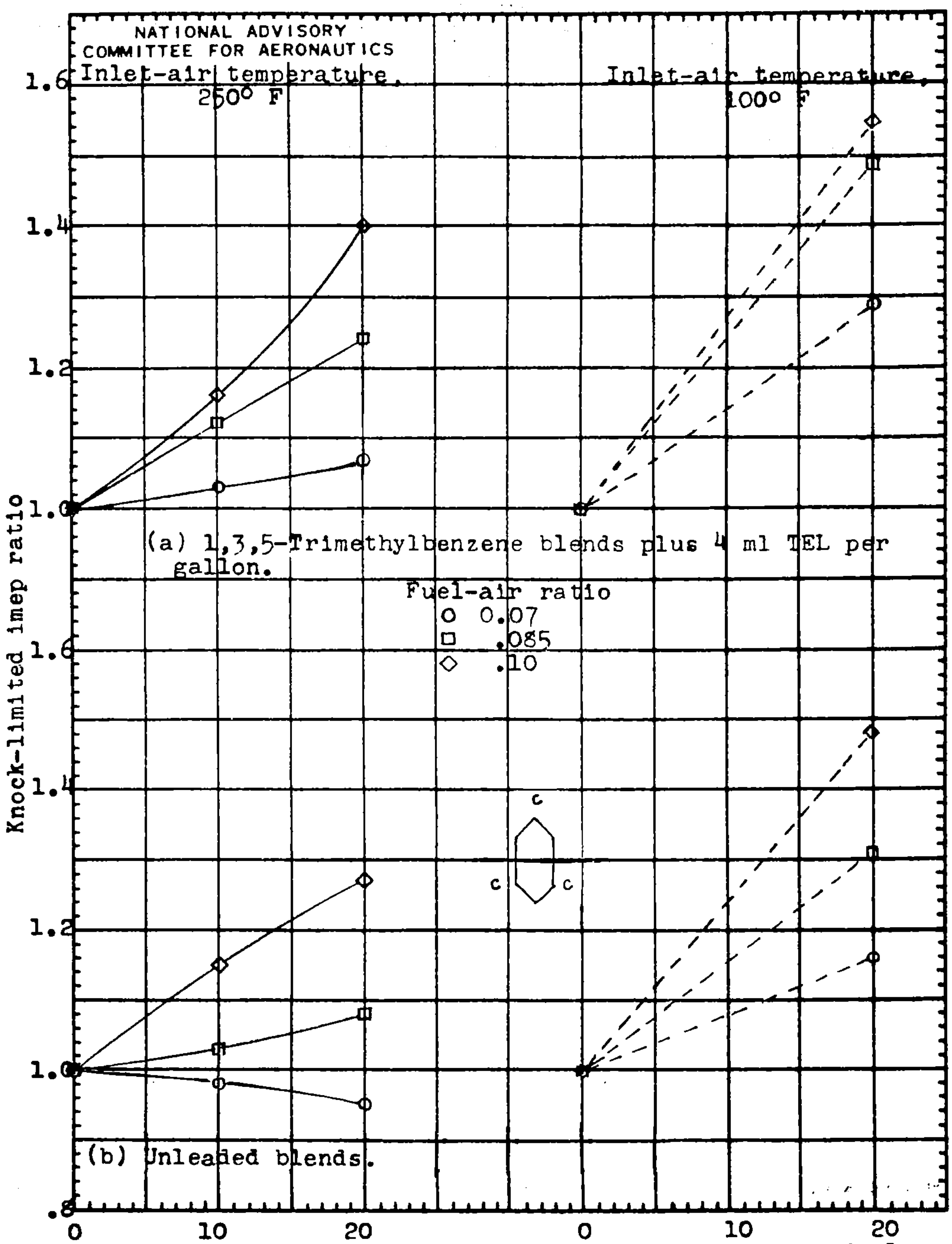


Figure 17. - The blending sensitivity of 1,3,5-trimethylbenzene in S-3 reference fuel. 17.6 engine.

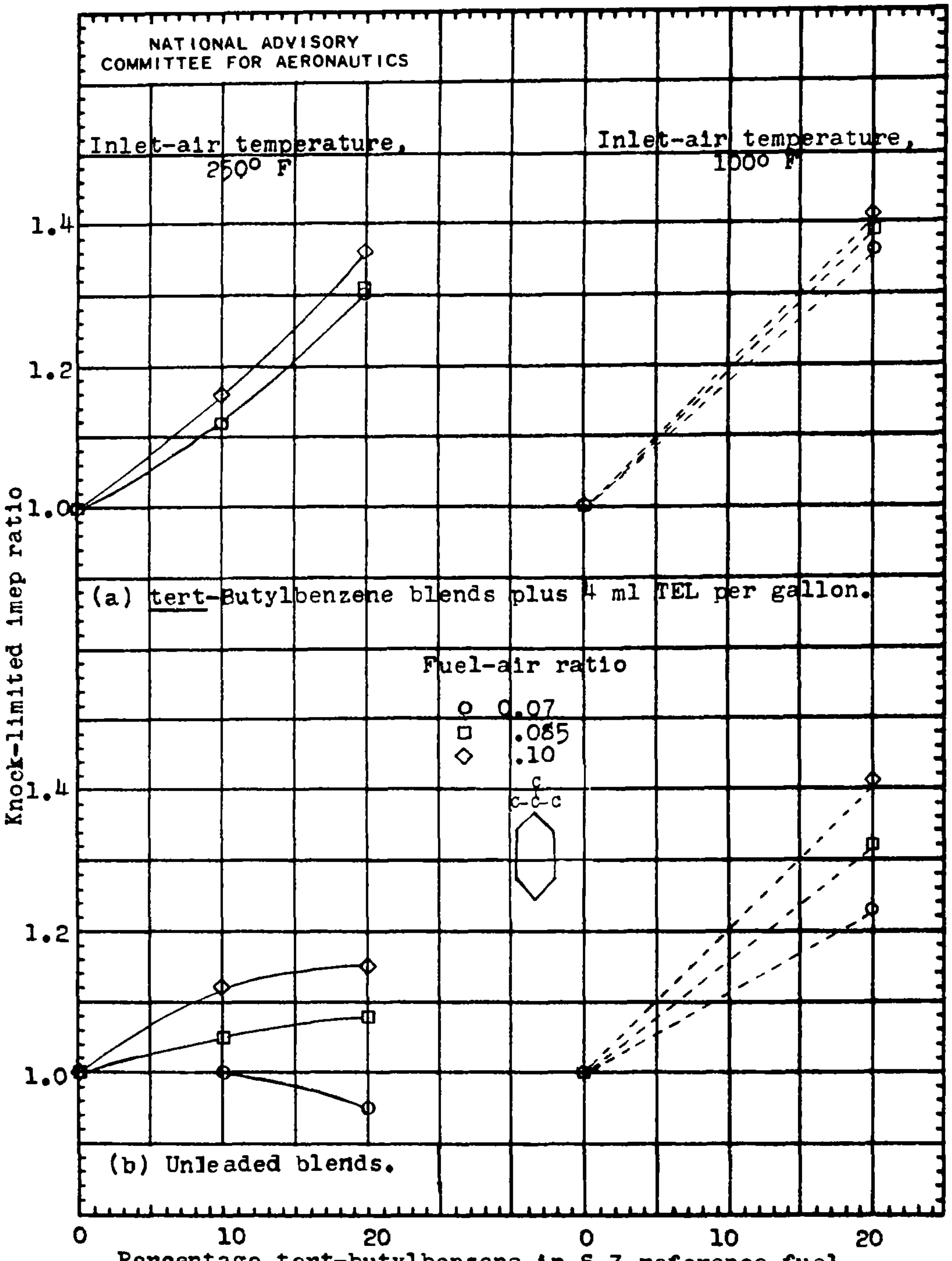


Figure 18. - The blending sensitivity of tert-butylbenzene in S-3 reference fuel. 17.6 engine.

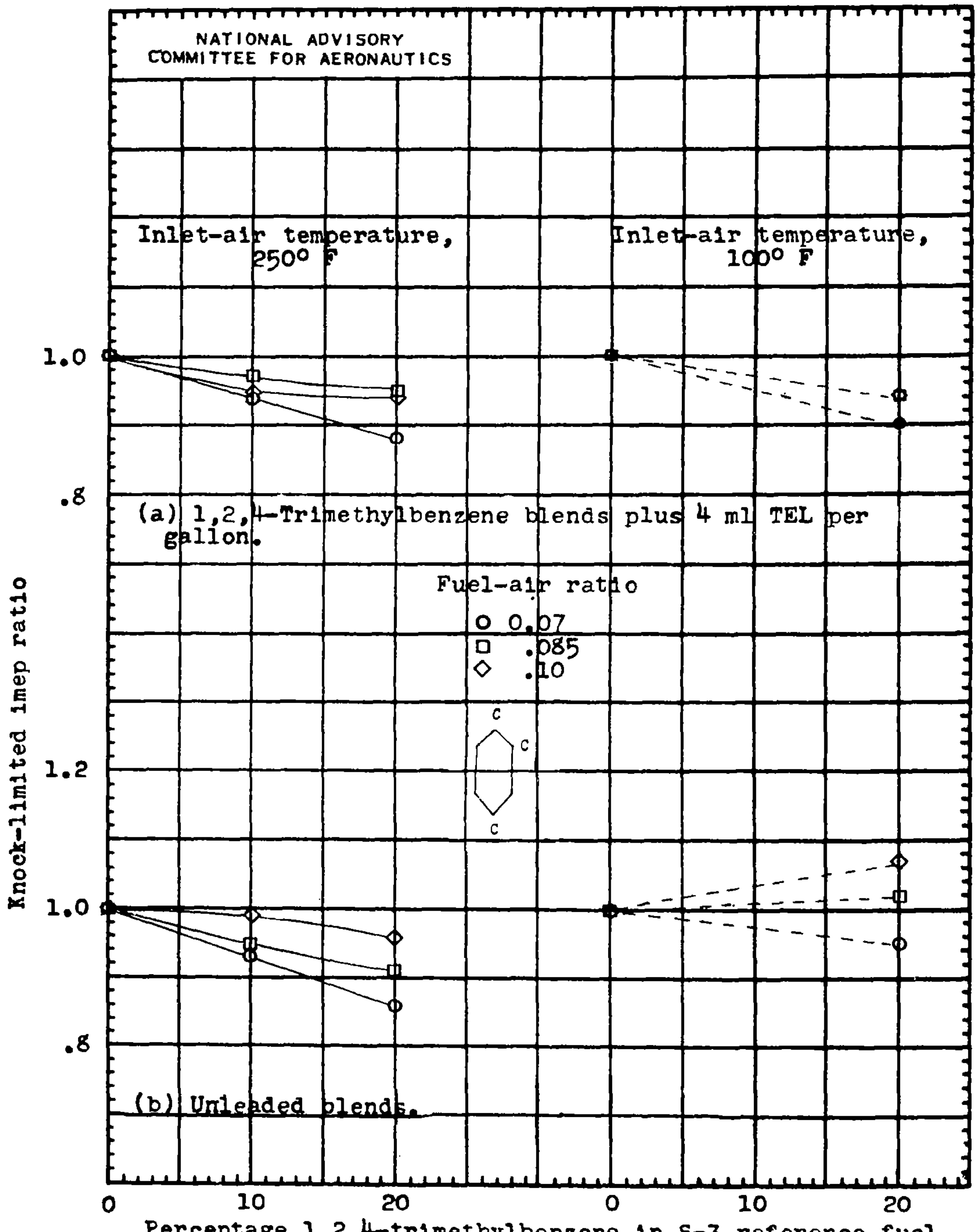


Figure 19. - The blending sensitivity of 1,2,4-trimethylbenzene in S-3 reference fuel. 17.6 engine.